

Progenitors of type Ia supernovae

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Abstract

Type Ia supernovae (SNe Ia) play an important role in astrophysics and are crucial for the studies of stellar evolution, galaxy evolution and cosmology. They are generally thought to be thermonuclear explosions of accreting carbon–oxygen white dwarfs (CO WDs) in close binaries, however, the nature of the mass donor star is still unclear. In this article, we review various progenitor models proposed in the past years and summarize many observational results that can be used to put constraints on the nature of their progenitors. We also discuss the origin of SN Ia diversity and the impacts of SN Ia progenitors on some fields. The currently favourable progenitor model is the single-degenerate (SD) model, in which the WD accretes material from a non-degenerate companion star. This model may explain the similarities of most SNe Ia. It has long been argued that the double-degenerate (DD) model, which involves the merger of two CO WDs, may lead to an accretion-induced collapse rather than a thermonuclear explosion. However, recent observations of a few SNe Ia seem to support the DD model, and this model can produce normal SN Ia explosion under certain conditions. Additionally, the sub-luminous SNe Ia may be explained by the sub-Chandrasekhar mass model. At present, it seems likely that more than one progenitor model, including some variants of the SD and DD models, may be required to explain the observed diversity of SNe Ia.

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1. Introduction

Type Ia supernova (SN Ia) explosions are among the most energetic events observed in the Universe. They are defined as those without hydrogen or helium lines in their spectra, but with strong SiII absorption lines around the maximum light (Filippenko, 1997). They appear to be good cosmological distance indicators due to their high luminosities and remarkable uniformity, and thus are used for determining the cosmological parameters (e.g. Ω_M and Ω_Λ ; Riess et al., 1998; Perlmutter et al., 1999). This leads to the discovery of the accelerating expansion of the Universe that is driven by the mysterious dark energy. SNe Ia are also a key part of our understanding of galactic chemical evolution owing to the main contribution of iron to their host galaxies (e.g. Gregg and Renzini, 1983; Matteucci and Gregg, 1986). In addition, they are accelerators of cosmic rays and as sources of kinetic energy in galaxy evolution processes (e.g. Helder et al., 2009; Powell et al., 2011). The use of SNe Ia as standard candles is based on the assumption that all SNe Ia have similar progenitors and are highly homogeneous. However, several key issues related to the nature of their progenitors and explosion mechanism are still not well understood (Branch et al., 1995; Hillebrandt and Niemeyer, 2000). This may directly affects the reliability of the results of the current cosmological model and galactic chemical evolution model.

When SNe Ia are used as distance indicators, the Phillips relation is adopted, which is a phenomenological linear relation between the absolute magnitude of SNe Ia and the magnitude difference from its *B*-band maximum to 15 days after that (Phillips, 1993). The Phillips relation is based on the SN Ia sample of low redshift Universe ($z < 0.05$) and assumed to be valid at high redshift. This assumption is precarious since there is still no agreement on the nature of their progenitors. If the properties of SNe Ia evolve with the redshift, the results for cosmology might be different. In addition, more observational evidence indicates that not all SNe Ia obey the Phillips relation (e.g. Wang et al., 2006).

Aside from the Phillips relation, many updated versions of this method are given to establish the relation between SN Ia intrinsic luminosities and the shape of their light curves. The stretch factor s method was proposed to measure the light curve shape by adjusting the scale on the time axis by a multiplicative factor (Perlmutter et al., 1997; Goldhaber et al., 2001). In addition, an empirical method based on multicolor light curve shapes has been developed to estimate the luminosity, distance, and total line-of-sight extinction of SNe Ia (Riess et al., 1998). Wang et al. (2005) presented a single post-maximum color parameter ΔC_{12} ($B - V$ color ~ 12 days after the *B*-band light maximum), which empirically describes almost the full range of the observed SN Ia luminosities and gives tighter correlations with their luminosities, but the underpinning physics is still not understood. Recently, Guy et al. (2005) used an innovative approach to constrain the spectral energy distribution of SNe Ia,

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parameterized continuously as a function of color and stretch factor s , and allow for the generation of light curve templates in arbitrary pass-bands. This method was known as the spectral adaptive light curve template method, which offers several practical advantages that make it easily applicable to high redshift SNe Ia. The k-corrections are built into the model but not applied to the data, which allows one to propagate all the uncertainties directly from the measurement errors.

It is widely accepted that SNe Ia arise from thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in close binaries (Hoyle and Fowler, 1960; Nomoto et al., 1997). This hypothesis is supported by the fact that the amount of energy observed in SN explosions is equal to the amount that would be produced in the conversion of carbon and oxygen into iron ($\sim 10^{51}$ erg; Thielemann et al., 2004). The energy released from the nuclear burning completely destroys the CO WD and produces a large amount of ^{56}Ni . The optical/infrared light curves are powered by the radioactive decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$. In order to trigger the carbon ignition, the mass of the CO WD must grow close to the Chandrasekhar (Ch) mass. When the WD increases its mass close to the Ch mass, it is thought to ignite near the center; at first the flame propagates subsonically as a deflagration, and in a second phase a detonation triggers, which propagates supersonically and completely destroys the CO WD (Hillebrandt and Niemeyer, 2000). The realistically conceivable way to make the WD grow to the Ch mass is via mass-transfer from a mass donor star in a close binary. However, the nature of the mass donor star in the close binary is still uncertain, and no progenitor system before SN explosion has been conclusively identified. Additionally, there is some observational evidence that a subset of SNe Ia have progenitors with a mass exceeding or below the standard Ch mass limit (e.g. Howell et al., 2006; Foley et al., 2009; Wang et al., 2008a).

Many progenitor models of SNe Ia have been proposed in the past years. The most popular progenitor models are single-degenerate (SD) and double-degenerate (DD) models. In Sect. 2, we review various progenitor models, including some variants of the SD and DD models proposed in the literature. We summarize some observational ways to test the current progenitor models in Sect. 3, and introduce some objects that may be related to the progenitors and the surviving companion stars of SNe Ia in Sect. 4. We discuss the origin of SN Ia diversity and the impacts of SN Ia progenitors on some research fields in Sects. 5 and 6, respectively. Finally, a summary is given in Sect. 7. For more discussions on these subjects, see previous reviews on SN Ia progenitors (e.g. Branch et al., 1995; Hillebrandt and Niemeyer, 2000; Livio, 2000; Nomoto et al., 2003; Podsiadlowski, 2010; Maoz and Mannucci, 2012).

2. Progenitor models

2.1. Single-degenerate model

In this model, a CO WD accretes hydrogen-rich or helium-rich material from a non-degenerate companion star, increases its mass to the Ch mass, and then explodes as a SN Ia (Whelan and Iben, 1973; Nomoto, 1982a). The SD model may explain

the similarities of most SNe Ia, since SN Ia explosions in this model occur when the CO WD increases its mass to the maximum stable mass (i.e. the Ch mass). In addition, the observed light curves and early time spectra of the majority of SNe Ia are in excellent agreement with the synthetic spectra of the SD Ch mass model (Nomoto et al., 1984; Höflich et al., 1996; Nugent et al., 1997).

The companion star in this model could be a main-sequence (MS) star or a subgiant star (WD + MS channel), or a red-giant star (WD + RG channel), or a helium star (WD + He star channel) (Hachisu et al., 1996, 1999a,b; Li and van den Heuvel, 1997; Langer et al., 2000; Han and Podsiadlowski, 2004; Fedorova et al., 2004; Meng et al., 2009; Wang et al., 2009a, 2010a). The main problem for this class of models is that it is generally difficult to increase the mass of the WD by accretion. Whether the WD can grow in mass depends crucially on the mass-transfer rate and the evolution of the mass-transfer rate with time. (1) If the rate is too high, the system may enter into a common envelope (CE) phase; (2) if the rate is too low, the nuclear burning is unstable that leads to nova explosions in which all the accreted matter is ejected. There is only a very narrow parameter range in which the WD can accrete H-rich or He-rich material and burn in a stable manner. This parameter range may be increased if the rotation affects the WD mass-accretion process (Yoon and Langer, 2004).

An essential element in this model is the optically thick wind assumption, which enlarges the parameter space for producing SNe Ia (Hachisu et al., 1996, 1999a,b; Li and van den Heuvel, 1997; Han and Podsiadlowski, 2004; Wang et al., 2009a, 2010a). In this assumption, taking a MS donor star for an example, if the mass-transfer rate from the MS star exceeds a critical value, \dot{M}_{cr} , it is assumed that the accreted H burns steadily on the surface of the WD and that the H-rich material is converted into He at the rate of \dot{M}_{cr} . The unprocessed matter is assumed to be lost from the binary system as an optically thick wind. However, this assumption is very sensitive to the Fe abundance, and it is likely that the wind does not work when the metallicity is lower than a certain value.¹

2.1.1. WD + MS channel

In the WD + MS channel (usually called the supersoft channel), a CO WD in a binary system accretes H-rich material from a MS or a slightly evolved subgiant star. The accreted H-rich material is burned into He, and then the He is converted to carbon and oxygen. When the CO WD increases its mass close to the Ch mass, it explodes as a SN Ia. Based on the evolutionary phase of the primordial primary (i.e. the massive star) at the beginning of the first Roche lobe overflow (RLOF), there are three evolutionary scenarios to form WD + MS systems and

¹At low enough metallicities (e.g. $Z < 0.002$), the optical depth of the wind would become small, and thus the wind-regulation mechanism would become ineffective (e.g. Kobayashi et al., 1998; Kobayashi and Nomoto, 2009). In this case, the binary system will pass through a CE phase before reaching the Ch mass. Thus, if this is true then there would be an obvious low-metallicity threshold for SNe Ia in comparison with SNe II. However, the metallicity threshold has not been found in observations (Prieto et al., 2008; Badenes et al., 2009a).

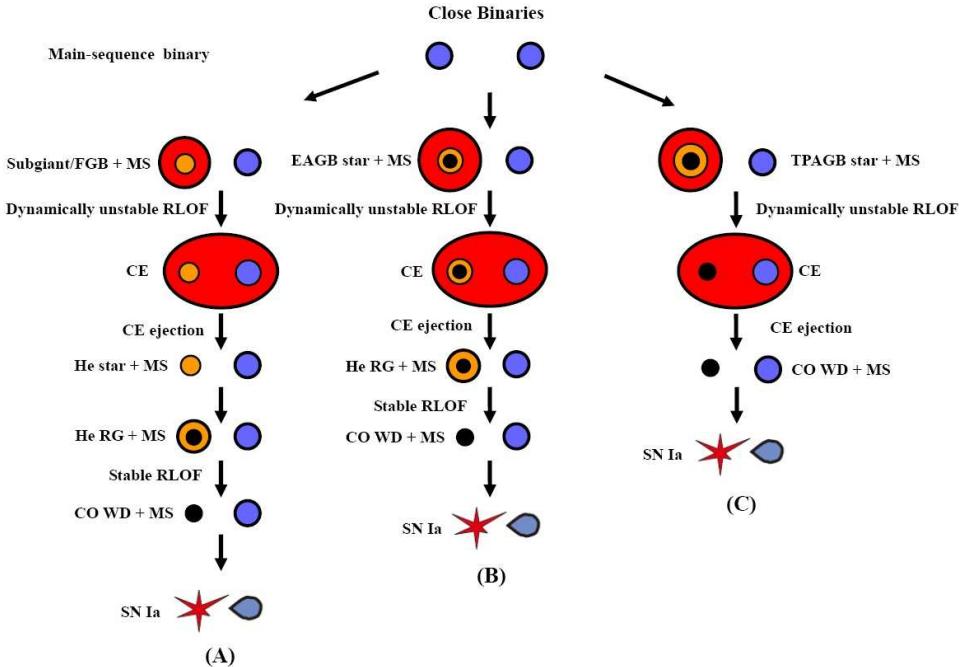


Figure 1: Binary evolutionary scenarios of the WD + MS channel for producing SNe Ia.

then produce SNe Ia (Fig. 1; for details see Wang et al., 2010a; also see Postnov and Yungelson, 2006; Meng et al, 2009).

Scenario A: The primordial primary first fills its Roche lobe when it is in the Hertzsprung gap (HG) or first giant branch (FGB) stage (i.e. Case B mass-transfer defined by Kippenhahn and Weigert, 1967). In this case, due to a large mass-ratio or a convective envelope of the mass donor star, a CE may be formed (Paczynski, 1976). After the CE ejection, the primary becomes a He star and continues to evolve. After the exhaustion of central He, the He star evolves to the RG stage. The He RG star that now contains a CO-core may fill its Roche lobe again due to the expansion itself, and transfer its remaining He-rich envelope onto the surface of the MS companion star, eventually leading to the formation of a CO WD + MS system. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 4.0\text{--}7.0 M_\odot$, $M_{2,i} \sim 1.0\text{--}2.0 M_\odot$, and $P^i \sim 5\text{--}30$ days, where $M_{1,i}$, $M_{2,i}$ and P^i are the initial masses of the primary and the secondary at zero age main-sequence (ZAMS), and the initial orbital period of the binary system.

Scenario B: If the primordial primary is on the early asymptotic giant branch (EAGB, i.e. He is exhausted in the center of the star while this star has a thick He-burning layer and the thermal pulses have not yet started), a CE may be formed due to the dynamically unstable mass-transfer. After the CE is ejected, a close He RG + MS binary may be produced; the binary orbit decays in the process of the CE ejection and the primordial primary may evolve to a He RG that contains a CO-core. The He RG may fill its Roche lobe and start mass-transfer, which is likely stable and results in a CO WD + MS system. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 2.5\text{--}6.5 M_\odot$,

$M_{2,i} \sim 1.5\text{--}3.0 M_\odot$ and $P^i \sim 200\text{--}900$ days.

Scenario C: The primordial primary fills its Roche lobe at the thermal pulsing asymptotic giant branch (TPAGB) stage. A CE is easily formed owing to the dynamically unstable mass-transfer during the RLOF. After the CE ejection, the primordial primary becomes a CO WD, then a CO WD + MS system is produced. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 4.5\text{--}6.5 M_\odot$, $M_{2,i} \sim 1.5\text{--}3.5 M_\odot$, and $P^i > 1000$ days.

Among the three evolutionary scenarios above, models predict that scenario A is the more significant route for producing SNe Ia (e.g. Wang et al., 2010a). The WD + MS channel has been identified in recent years as supersoft X-ray sources and recurrent novae (van den Heuvel et al., 1992; Rappaport et al., 1994; Meng and Yang, 2010a). Many works have been concentrated on this channel. Some authors studied the WD + MS channel with a simple analytical method to treat binary interactions (e.g. Hachisu et al., 1996, 1999a, 2008). Such analytic prescriptions may not describe some mass-transfer phases well enough, especially those occurring on a thermal time-scale. Li and van den Heuvel (1997) studied this channel from detailed binary evolution calculation with two WD masses (e.g. 1.0 and $1.2 M_\odot$). Langer et al. (2000) investigated this channel for metallicities $Z = 0.001$ and 0.02 , but they only studied Case A evolution (mass-transfer during the central H-burning phase). Han and Podsiadlowski (2004) carried out a detailed study of this channel including Case A and early Case B for $Z = 0.02$. The Galactic SN Ia birthrate from this study is $0.6\text{--}1.1 \times 10^{-3} \text{ yr}^{-1}$. Following the studies of Han and Podsiadlowski (2004), Meng et al. (2009) studied the WD + MS

channel comprehensively and systematically at various metallicities.

King et al. (2003) inferred that the mass-accretion rate onto the WD during dwarf nova outbursts can be sufficiently high to allow steady nuclear burning of the accreted matter and growth of the WD mass. Recently, Xu and Li (2009) also emphasized that, during the mass-transfer through the RLOF in the evolution of WD binaries, the accreted material can form an accretion disc surrounding the WD, which may become thermally unstable (at least during part of the mass-transfer lifetime), i.e. the mass-transfer rate is not equivalent to the mass-accretion rate onto the WD. By considering the effect of the thermal-viscous instability of accretion disk on the evolution of WD binaries, Wang et al. (2010a) recently enlarged the regions of the WD + MS channel for producing SNe Ia, and confirmed that WDs in this channel with an initial mass as low as $0.6 M_{\odot}$ can accrete efficiently and reach the Ch mass limit. Based on a detailed binary population synthesis (BPS) approach,² they found that this channel is effective for producing SNe Ia (up to $1.8 \times 10^{-3} \text{ yr}^{-1}$ in the Galaxy), which can account for about 2/3 of the observations (see also Meng and Yang, 2010a). However, the parameter regions for producing SNe Ia in this model depend on many uncertain input parameters, in particular the duty cycle during the nova outbursts that is still poorly known. Additionally, whether dwarf nova outbursts can increase the mass of a WD is still a problem (e.g. Hachisu et al., 2010).

2.1.2. WD + RG channel

The mass donor star in this channel is a RG star, which is also called the symbiotic channel. There is one evolutionary scenario that can form WD + RG binaries and then produce SNe Ia (Fig. 2; for details see Wang et al, 2010a). Compared with the WD + MS channel, SNe Ia in the WD + RG channel are from wider primordial binaries. The primordial primary fills its Roche lobe at the TPAGB stage. A CE is easily formed due to the dynamically unstable mass-transfer during the RLOF. After the CE ejection, the primordial primary becomes a CO WD. The MS companion star continues to evolve until the RG stage, i.e. a CO WD + RG binary is formed. For the WD + RG systems, SN Ia explosions occur for the ranges $M_{1,i} \sim 5.0\text{--}6.5 M_{\odot}$, $M_{2,i} \sim 1.0\text{--}1.5 M_{\odot}$, and $P^i > 1500$ days.

Unfortunately, the WD + RG binary usually undergoes a CE phase when the RG star overflows its Roche lobe. More importantly, the appropriate initial parameter space for producing SNe Ia in this channel is too small. Thus, WD + RG binaries seem to unlikely become a major way to form SNe Ia. Many authors claimed that the SN Ia birthrate via the WD + RG channel is much lower than that from the WD + MS channel (Yungelson and Livio, 1998; Han and Podsiadlowski, 2004; Lü et al., 2006; Wang et al., 2010a). The lowest initial WD mass in this channel for producing SNe Ia is about $1.0 M_{\odot}$ (e.g. Wang and Han, 2010a). In order to stabilize the mass-transfer process and

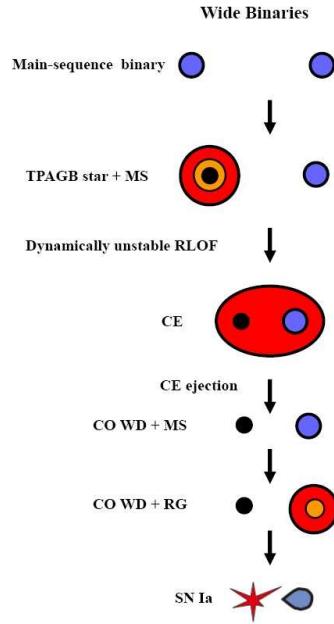


Figure 2: Similar to Fig. 1, but for the WD + RG channel.

avoid the formation of the CE, Hachisu et al. (1999b) assumed a mass-stripping model in which a stellar wind from the WD collides with the RG surface and strips some of the mass from the RG. They obtained a high SN Ia birthrate ($\sim 0.002 \text{ yr}^{-1}$) for this channel. Here, Hachisu et al. (1999b) used equation (1) of Iben and Tutukov (1984) to estimate the birthrate, i.e.

$$\nu = 0.2 \Delta q \int_{M_A}^{M_B} \frac{dM}{M^{2.5}} \Delta \log A \text{ yr}^{-1}, \quad (1)$$

where Δq , $\Delta \log A$, M_A and M_B are the appropriate ranges of the initial mass ratio, the initial separation, and the lower and upper limits of the primary mass for producing SNe Ia in units of solar masses, respectively. However, the birthrate is probably overestimated, since some parameter spaces considered to produce SNe Ia in equation (1) may not contribute to SNe Ia.

In symbiotic systems, WDs can accrete a fraction of the stellar wind from cool giants. It is generally believed that the stellar wind from a normal RG is expected to be largely spherical owing to the spherical stellar surface and isotropic radiation. However, the majority (>80%) of the observed planetary nebulae are found to have aspherical morphologies (Zuckerman and Aller, 1986). Additionally, the stellar winds from cool giants in symbiotic systems flow out in two ways: an equatorial disc and a spherical wind. In this context, by assuming an aspherical stellar wind with an equatorial disk from a RG, Lü et al. (2009) investigated the production of SNe Ia via the symbiotic channel. They estimated that the Galactic SN Ia birthrate via this channel is between $2.27 \times 10^{-5} \text{ yr}^{-1}$ and 1.03×10^{-3} , and the theoretical SN Ia delay time (between the star formation and SN explosion) has a wide range from 0.07 to 5 Gyr. However, these results are greatly affected by the outflow velocity and the mass-loss rate of the equatorial disk.

²BPS is a useful tool to simulate a large population of stars or binaries and can help understand processes that are difficult to observe directly or to model in detail (e.g. Han et al., 1995; Yungelson and Livio, 2000; Nelemans et al., 2001).

The stellar wind from RG stars might be enhanced by tidal or other interactions with a companion. Tout and Eggleton (1988) brought the tidally enhanced stellar wind assumption to explain the mass inversion in RS CVn binaries. This assumption has been widely used to explain many phenomena related to giant star evolution in binaries (e.g. Han, 1998; van Winckel, 2003). The tidally enhanced stellar wind assumption has two advantages in the studies of symbiotic systems: (1) The WD may grow in mass substantially by accretion from stellar wind before RLOF; (2) the mass-transfer may be stabilized because the mass ratio ($M_{\text{giant}}/M_{\text{WD}}$) can be much reduced at the onset of RLOF. By adopting the tidally enhanced stellar wind assumption, Chen et al. (2011) recently argued that the parameter space of SN Ia progenitors can be extended to longer orbital periods for the WD + RG channel (compared to the mass-stripping model of Hachisu et al., 1999b), and thus increase the birthrate up to $6.9 \times 10^{-3} \text{ yr}^{-1}$, which is also probably overestimated due to the use of equation (1). Additionally, the parameter space of SN Ia progenitors strongly depends on the tidal wind enhancement parameter B_w that is still poorly known.

In a variant of the symbiotic channel, the mass-transfer from carbon-rich AGB stars with WD components can occur via stellar winds or RLOF (Iben and Tutukov, 1985). It has been suggested that an AGB donor star is in the progenitor system of SN 2002ic, which is an atypical SN Ia with evidence for substantial amounts of hydrogen associated with the system (Hamuy et al., 2003). Recently, Chiotellis et al. (2012) presented a WD with an AGB donor star for the SN remnant (SNR) of SN 1604, also known as Kepler's SNR. They argued that its main features can be explained by the model of a symbiotic binary consisting of a WD and an AGB donor star with an initial mass of $4-5 M_{\odot}$. Detailed calculations of binary evolutionary model are needed to understand whether these WD components in WD + AGB binaries can result in SN Ia explosions.

2.1.3. WD + He star channel

A CO WD may also accrete helium-rich material from a He star or a He subgiant to increase its mass to the Ch mass, which is also known as the He star donor channel. There are three evolutionary scenarios to form WD + He star systems and then produce SNe Ia (see Fig. 3; for details see Wang et al., 2009b).

Scenario A: The primordial primary first fills its Roche lobe when it is in the HG or FGB stage. At the end of the RLOF, the primary becomes a He star and continues to evolve. After the exhaustion of central He, the He star evolves to the RG stage. The He RG star that now contains a CO-core may fill its Roche lobe again due to the expansion of itself, and transfer its remaining He-rich envelope to the MS companion star, eventually leading to the formation of a CO WD + MS system. After that, the MS companion star continues to evolve and fills its Roche lobe in the HG or FGB stage. A CE is possibly formed due to the dynamically unstable mass-transfer. If the CE can be ejected, a close CO WD + He star system is then produced. The CO WD + He star system continues to evolve, and the He star may fill its Roche lobe again (due to the orbit decay induced by the gravitational wave radiation or the expansion of the He star itself), and transfer some material onto the surface

of the CO WD. The accreted He may be converted into carbon and oxygen via the He-shell burning, and the CO WD increases in mass and explodes as a SN Ia when its mass reaches the Ch mass. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 5.0-8.0 M_{\odot}$, $M_{2,i} \sim 2.0-6.5 M_{\odot}$ and $P^i \sim 10-40$ days.

Scenario B: If the primordial primary is on the EAGB stage at the onset of the RLOF, a CE may be formed due to the dynamically unstable mass-transfer. After the CE is ejected, a close He RG + MS binary may be produced; the binary orbit decays in the procedure of the CE ejection and the primordial primary becomes a He RG. The He RG may fill its Roche lobe and start the mass-transfer, which is likely stable and results in a CO WD + MS system. The subsequent evolution of this system is similar to scenario A above, and may form a CO WD + He star system and finally produce a SN Ia. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 6.0-6.5 M_{\odot}$, $M_{2,i} \sim 5.5-6.0 M_{\odot}$ and $P^i \sim 300-1000$ days.

Scenario C: The primordial primary fills its Roche lobe at the TPAGB stage, and the companion star evolves to the He-core burning stage. A double-core CE may be formed owing to the dynamically unstable mass-transfer during the RLOF. After the CE ejection, the primordial primary becomes a CO WD, and the companion star is a He star at the He-core burning stage, i.e. a CO WD + He star system is formed. The subsequent evolution of this system is similar to that in the above two scenarios, i.e. a SN Ia may be produced. For this scenario, SN Ia explosions occur for the ranges $M_{1,i} \sim 5.5-6.5 M_{\odot}$, $M_{2,i} \sim 5.0-6.0 M_{\odot}$ and $P^i > 1000$ days.

SNe Ia from the He star donor channel can neatly avoid H lines, consistent with the defining spectral characteristic of most SNe Ia. Yoon and Langer (2003) followed the evolution of a WD + He star binary with a $1.0 M_{\odot}$ WD and a $1.6 M_{\odot}$ He star in a 0.124 d orbit. In this binary, the WD accretes He from the He star and grows in mass to the Ch mass. Based on the optically thick wind assumption, Wang et al. (2009a) systematically studied the He star donor channel. In the study, they carried out binary evolution calculations of this channel for about 2600 close WD + He star binaries. The study showed the initial parameter spaces for the progenitors of SNe Ia, and found that the minimum mass of CO WD for producing SNe Ia in this channel may be as low as $0.865 M_{\odot}$. By using a detailed BPS approach, Wang et al. (2009b) found that the Galactic SN Ia birthrate from this channel is $\sim 0.3 \times 10^{-3} \text{ yr}^{-1}$ and this channel can produce SNe Ia with short delay times ($\sim 45-140$ Myr). Wang and Han (2010b) also studied the He star donor channel with different metallicities. For a constant star-formation galaxy (like our own galaxy), they found that SN Ia birthrates increase with metallicity. If a single starburst is assumed (like in an elliptical galaxy), SNe Ia occur systematically earlier and the peak value of the birthrate is larger for a higher metallicity.

2.2. Double-degenerate model

In the DD model, SNe Ia arise from the merging of two close CO WDs that have a combined mass larger than or equal to the Ch mass (Tutukov and Yungelson, 1981; Iben and Tutukov, 1984; Webbink, 1984). Both CO WDs are brought together by

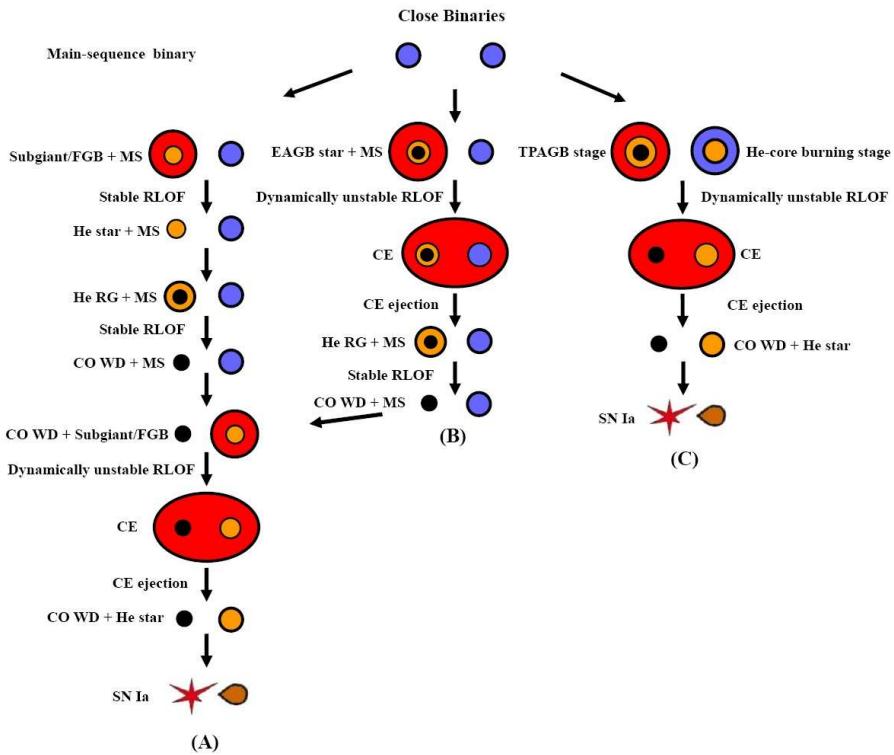


Figure 3: Similar to Fig. 1, but for the WD + He channel.

gravitational wave radiation on a timescale t_{GW} (Landau and Lifshitz, 1971),

$$t_{\text{GW}}(\text{yr}) = 8 \times 10^7 (\text{yr}) \times \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P^{8/3}(\text{h}), \quad (2)$$

where P is the orbital period in hours, t_{GW} in years and M_1, M_2 in M_\odot . The delay time from the star formation to the occurrence of a SN Ia is equal to the sum of the timescale that the secondary star becomes a WD and the orbital decay time t_{GW} . For the DD model, there are three binary evolutionary scenarios to form double CO WD systems and then produce SNe Ia, i.e. stable RLOF plus CE ejection scenario, CE ejection plus CE ejection scenario and exposed core plus CE ejection scenario (for details see Han, 1998).

The DD model has the advantage that the theoretically predicted merger rate is quite high, consistent with the observed SN Ia birthrate (e.g. Yungelson et al., 1994; Han, 1998; Nelemans et al., 2001; Ruiter et al., 2009; Wang et al., 2010b).³ Importantly, this model can naturally explain the lack of H or He emission in the spectra of SNe Ia. As an additional argument in favor of the DD model, one may consider this model to explain some observed super-luminous SNe Ia (for more discussions

see Sect. 2.3.2). Furthermore, there are some double WD progenitor candidates that have been found in observations, and recent observations of a few SNe Ia seem to support the DD model (for more discussions see Sect. 3). However, the DD model has difficulties in explaining the similarities of most SNe Ia, since the merger mass in this model varies for different binaries and has a relatively wide range ($\sim 1.4 - 2.0 M_\odot$; Wang et al., 2010b).

Most importantly, the merger of two WDs may result in an accretion-induced collapse to form a neutron star rather than a thermonuclear explosion (Nomoto and Iben, 1985; Saio and Nomoto, 1985; Timmes et al., 1994). In the process of a double-WD merger, once the less massive WD fills its Roche lobe, it is likely to be disrupted and rapidly accreted by the more massive one. Meanwhile, the less massive WD is transformed into a disk-like structure around the more massive companion. It is usually assumed that in this configuration the temperature maximum is located at the “disk-dwarf” interface and that carbon burning starts there. In this process, the carbon burning front propagates inward and then the CO WD is transformed into an O-Ne-Mg WD, which collapses to form a neutron star by electron capture on ^{24}Mg .

There may be some parameter ranges where the accretion-induced collapse can be avoided (e.g. Piersanti et al., 2003; Yoon et al., 2007). Piersanti et al. (2003) suggested that the double WD merger process could be quite violent, and might lead to a SN Ia explosion under the right conditions. Pakmor et al. (2010) argued that the violent mergers of two equal-

³Badenes and Maoz (2012) recently calculated the merger rate of binary WDs in the Galactic disk based on the observational data in the Sloan Digital Sky Survey. They claimed that there are not enough double WD systems with the super-Ch masses to reproduce the observed SN Ia birthrate in the context of the DD model.

mass CO WDs ($\sim 0.9 M_{\odot}$, critical conditions for the successful initiation of a detonation) can be obtained, and may explain the formation of sub-luminous 1991bg-like objects. Although the light curve from the merger model is broader than that of SN 1991bg-like objects, the synthesized spectra, red color and low expansion velocities are all close to those observed for SN 1991bg-like objects (Pakmor et al., 2010). In a further study, Pakmor et al. (2011) claimed that a high mass-ratio is required for this model to work; for a primary mass of $0.9 M_{\odot}$ a mass-ratio of at least about 0.8. This result will affect the potential SN Ia birthrate of the DD model. We note that van Kerkwijk et al. (2010) came to a similar conclusion before Pakmor et al. (2011), but that was in turn partially based on Pakmor et al. (2010) and Lorín-Aguilar et al. (2009). Adopting the results of Pakmor et al. (2011) with a detailed BPS approach, Meng et al. (2011) estimated that the sub-luminous events from this model may only account for not more than 1% of all SNe Ia.

Recently, by assuming that the moment at which the detonation forms is an artificial parameter, Pakmor et al. (2012) presented a fully three-dimensional simulation of a violent merger of two CO WDs with masses of $0.9 M_{\odot}$ and $1.1 M_{\odot}$, by combining very high resolution and the exact initial conditions. They estimated that the simulation produces about $0.62 M_{\odot}$ of ^{56}Ni , and the synthetic multi-color light curves show good agreement with those observed for normal SNe Ia. Due to the small number of such massive systems available, this model may only contribute a small fraction to the observed population of normal SNe Ia. Future studies are needed to explore the parameter space of different WD masses and mass ratios in this scenario for normal SNe Ia, which is important in BPS studies.

2.3. Potential progenitor models

Besides the SD and DD models above, some variants of SD and DD models have been proposed to explain the observed diversity of SNe Ia, such as the sub-Ch mass model, the super-Ch mass model, the single star model, the delayed dynamical instability model, the spin-up/spin-down model, the core-degenerate model, the model of the collisions between two WDs, and the model of WDs near black holes, etc.

2.3.1. Sub-Chandrasekhar mass model

In this model, a CO WD accumulates a $\sim 0.15 M_{\odot}$ He layer with a total mass below the Ch mass (Nomoto 1982b; Woosley et al., 1986). In order to achieve the central densities necessary to produce iron-peak elements, the WD in this model needs a narrow mass range of $\sim 0.9 - 1.1 M_{\odot}$. The He may ignite off-center at the bottom of the He layer, resulting in an event known as Edge Lit Detonation (or Indirect Double Detonation). In this process, one detonation propagates outward through the He layer, while an inward propagating pressure wave compresses the CO core that ignites off-center, followed by an outward detonation (e.g. Livne, 1990; Höflich and Khokhlov, 1996). It is possible that sub-luminous 1991bg-like objects may be explained by this model (Branch et al., 1995). Unfortunately, the sub-Ch mass model has difficulties in matching the observed light curves and spectroscopy of SNe Ia (Höflich and Khokhlov,

1996; Nugent et al., 1997), likely owing to the thickness of the He layer.

Recently, Shen and Bildsten (2009) argued that, under some suitable conditions, a detonation in the WD might be achieved for even lower He layer masses than that in previous studies. By assuming that a detonation is successfully triggered in the He layer, Fink et al. (2010) claimed that the double detonations in sub-Ch mass WDs with low-mass He layers can be a robust explosion, leading to normal SN Ia brightness. Recent studies involving the sub-Ch mass WDs with subsequent nucleosynthesis and radiative transfer calculations also indicate that the sub-Ch mass model could account for the range of the observed SN Ia brightness (Sim et al., 2010; Kromer et al., 2010). Additionally, BPS studies by Ruiter et al. (2009) predicted that there are a sufficient number of binaries with sub-Ch primary WDs to explain the observed birthrate of SNe Ia. However, it must be noted that it is difficult for the sub-Ch mass model to explain the similarities observed in most SNe Ia (e.g. Branch et al., 1995).

2.3.2. Super-Chandrasekhar mass model

The ^{56}Ni mass deduced from some SN Ia explosions strongly suggests the existence of super-Ch mass progenitors. SN 2003fg was observed to be 2.2 times over-luminous than a normal SN Ia, and the amount of ^{56}Ni was inferred to be $1.3 M_{\odot}$, which requires a super-Ch mass WD explosion ($\sim 2.1 M_{\odot}$; Howell et al., 2006). Following the discovery of SN 2003fg, three 2003fg-like events were also discovered, i.e. SN 2006gz (Hicken et al., 2007), SN 2007if (Scalzo et al., 2010; Yuan et al., 2010), and SN 2009dc (Yamanaka et al., 2009; Tanaka et al., 2010; Silverman et al., 2011). These super-luminous SNe Ia may raise the possibility that more than one progenitor model may lead to SNe Ia.

It is usually assumed that these super-luminous SNe Ia are from the mergers of double WD systems, where the total mass of the DD systems is over the Ch mass. Meanwhile, a super-Ch WD may be also produced by a SD system, where the massive WD is supported by its rapid rotation, e.g. Maeda and Iwamoto (2009) claimed that the properties of SN 2003fg may be consistent with the aspherical explosion of a super-Ch WD, which is supported by its rapid rotation. Yoon and Langer (2004) argued that WDs can rotate differentially for high mass-accretion rates of $3.0 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. By adopting the results of Yoon and Langer (2004), Chen and Li (2009) calculated the evolution of close binaries consisting of a CO WD and a MS star, and obtained the initial parameter space for super-Ch mass SN Ia progenitors. Within this parameter space, Meng et al. (2011) estimated that the upper limit of the contribution rate of these super-luminous SNe Ia to all SN Ia is less than 0.3%. Hachisu et al. (2012) recently made a comprehensive study of these super-luminous SNe Ia via the WD + MS channel, and suggested that these SNe Ia are born in a low metallicity environment as more massive initial CO WDs are required in this model. Meanwhile, Liu et al. (2010) also studied the He star donor channel to the formation of super-luminous SNe Ia by considering the effects of rapid differential rotation on the accreting WD.

Aside from the differential rotation, a super-Ch WD may also be supported by the WDs with strong magnetic fields due to the lifting effect. It has been found that $\sim 10\%$ of WDs have magnetic fields stronger than 1 MG (Liebert et al., 2003, 2005; Wickramasinghe and Ferrario, 2005). The mean mass of these magnetic WDs is $\sim 0.93 M_{\odot}$, compared with the mean mass of all WDs that is $\sim 0.56 M_{\odot}$ (e.g. Parthasarathy et al., 2007). Thus, the magnetic WDs are more easily to reach the Ch mass limit by accretion. The magnetic field may also affect some properties of SD progenitor systems, e.g. the mass-transfer rate, the critical mass-accretion rate and the thermonuclear reaction rate, etc. However, these effects are still unclear. Further studies are thus needed.

2.3.3. Single star model

Single star progenitor models have been considered by Iben and Renzini (1983) and Tout et al. (2008). In the absence of mass-loss, single massive star less than about $7 M_{\odot}$ will develop a degenerate CO-core when the star evolves to the AGB stage. The mass growing rate of the CO-core is controlled by the rate of the double shell burning. If the CO-core can grow to the Ch mass, it will produce a SN Ia. Under certain conditions, Tout et al. (2008) claimed that carbon can ignite at the center of the CO-core and the subsequent explosion would appear as a SN Ia. These single star progenitors are likely to be over $2 M_{\odot}$, so this kind of SNe Ia should be associated with younger galaxies with recent star formation. The single star model was also proposed to explain the strongly circumstellar-interacting SN 2002ic (Hamuy et al., 2003).

An important theoretical argument for this model is that the H-rich envelope in AGB star may be lost in a superwind before the CO-core grows to the Ch mass, based on the envelope ejection criteria by Han et al. (1994) and Meng et al. (2008). Another problem for this model is that there should be far more SNe Ia than observed if a single star can naturally experience thermonuclear explosion.

2.3.4. Delayed dynamical instability model

This model is a variant of the WD + MS channel, which requires that the donor star is initially a relatively massive MS star ($\sim 3 M_{\odot}$) and that the system has experienced a delayed dynamical instability, resulting in a large amount of mass-loss from the system in the last a few 10^4 yr before SN explosion (Han and Podsiadlowski, 2006). The delayed dynamical instability model can reproduce the inferred H-rich circumstellar environment, most likely with a disc-like geometry. Han and Podsiadlowski (2006) claimed that the unusual properties of SN 2002ic can be understood by the delayed dynamical instability model. Observationally, this model seems to be consistent with SN 2005gj (another 2002ic-like object) found by Nearby Supernova Factory observations (Aldering et al., 2006).

However, in order for this model to be feasible, it requires a larger mass-accretion efficiency onto the WD than is assumed in present parametrizations. Based on a detailed BPS simulation, Han and Podsiadlowski (2006) estimated that not more than 1% SNe Ia should belong to this subclass of SNe Ia. Since this model requires an intermediate-mass secondary star, these SNe

Ia should only be found in stellar populations with relatively recent star formation (e.g. with the last $\sim 3 \times 10^8$ yr).

2.3.5. Spin-up/spin-down model

In the SD model, since the continued accretion of angular momentum can prevent the explosion of a WD, Justham (2011) recently argued that it may be natural for the mass donor stars in the SD model to exhaust their envelopes and shrink rapidly before SN explosion, which may explain the lack of H or He in the spectra of SNe Ia, often seen as troublesome for the SD progenitor model. Di Stefano et al. (2011) also suggested that the CO WD is likely to achieve fast spin periods as the accreted mass carries angular momentum, which can increase the critical mass, M_{cr} , needed for SN explosion. When the M_{cr} is higher than the maximum mass obtained by the WD, the WD must spin down before it explodes. This leads to a delay between the time at which the WD has completed its epoch of mass gain and the time of the SN explosion. However, the spin-down time is still unclear, which may have a large range from < 1 Myr to > 1 Gyr (Lindblom, 1999; Yoon and Langer, 2005). The spin-down time may be important for the formation of the SNe Ia with long delay times.

The spin-up/spin-down model may provide a route to explain the similarities and the diversity observed in SNe Ia. However, the birthrates, the delay times and the distributions of SN Ia explosion masses are still uncertain in this model. A detailed BPS studies are needed for this.

2.3.6. Core-degenerate model

Kashi and Soker (2011) recently investigated some possible outcomes of double WD mergers, in which these two components are made of CO. Most simulations and calculations of double WD mergers assume that a merger occurs a long time after the CE ejection, when these two WDs are already cold. In this model, Kashi and Soker (2011) proposed that, a merger occurs within the final stages of the CE, whereas the CO-core is still hot. The merged hot core is supported by rotation until it slows down through the magnetic dipole radiation, and finally explodes. Kashi and Soker (2011) named this as the core-degenerate model, and claimed that this is another scenario to form a massive WD with super-Ch mass that might explode as a super-luminous SN Ia (see also Ilkov and Soker, 2012). A BPS study is required to determine the birthrate and delay time of this model, which are then compared with observations.

2.3.7. Collisions of two WDs

The WD number densities in globular clusters allow ~ 10 – 100 times collisions between two WDs per year, and the observations of globular clusters in the nearby S0 galaxy NGC 7457 have detected a likely remnant of SNe Ia (Chomiuk et al., 2008). In this context, Raskin et al. (2009) explored collisions between two WDs as a way for producing SNe Ia. They carried out simulations of the collisions between two WDs ($\sim 0.6 M_{\odot}$) at various impact parameters (the vertical separation of the centers of the WDs). By taking impact parameters less than half of the WD radius before collision, they claimed that the SN explosions induced by such collisions can produce

$\sim 0.4 M_{\odot}$ of ^{56}Ni , making such objects potential candidates for sub-luminous SN Ia events. In a further study, Raskin et al. (2010) argued that two WD collisions could also realize super-Ch mass WD explosions (see also Rosswog et al., 2009a). However, this model predicts a very aspherical explosion, inconsistent with the small continuum polarization level in one of the observed super-luminous SNe Ia (i.e. SN 2009dc; see Tanaka et al., 2010). We note that collisions between two WDs are likely to happen in the dense environments of globular clusters, however the expected of which is still less frequent than that of the double WD mergers.

2.3.8. WDs near black holes

Wilson and Mathews (2004) proposed a new mechanism for producing SNe Ia, in which relativistic terms enhance the self-gravity of a CO WD when it passes near a black hole. They suggested that this relativistic compression can cause the central density of the WD to exceed the threshold for pycnonuclear reactions so that a thermonuclear runaway occurs. Dearborn et al. (2005) speculated that this mechanism might explain the observed ‘mixed-morphology’ of the Sgr A East SN remnant in the Galactic center. For more studies of this mechanism see Rosswog et al. (2008, 2009b). Due to the expected low rate of a WD passing near a black hole, the expected SN Ia birthrate from this mechanism should be significantly lower than that from normal SNe Ia.

3. Observational constraints

Many observational results can be used to constrain the SN Ia progenitor models, e.g. the properties of SN Ia host galaxies, the birthrates and delay times of SNe Ia, the candidate progenitors of SNe Ia, the surviving companion stars of SNe Ia, the stripped mass of companions due to SN explosion, the signatures of gas outflows from some SN Ia progenitor systems, the wind-blown cavity in SN remnant, the early optical and UV emission of SNe Ia, the early radio and X-ray emission of SNe Ia, and the pre-explosion images and spectropolarimetry of SNe Ia, etc.

3.1. SN Ia host galaxies

There are some observational clues from the galaxies that host SNe Ia. SNe Ia have been known to occur both in young and old stellar populations (e.g. Branch and van den Bergh, 1993), which implies that there is a time delay between the star formation and the SN explosion, ranging from much less than 1 Gyr to at least several Gyr. In addition, SNe Ia in old population tend to be less luminous, and the most luminous SNe Ia appear to prefer young populations with recent star formation (Hamuy et al., 1996; Wang et al. 2008a). This indicates that the age of SNe Ia is an important parameter controlling at least part of SN Ia diversity. It was also established that super-luminous SNe Ia preferably occur in relatively metal poor environments with low-mass host galaxies, whereas sub-luminous SNe Ia occur in non star-forming host galaxies with large stellar masses, such as elliptical galaxies (Neill et al., 2009; Taubenberger et al., 2011).

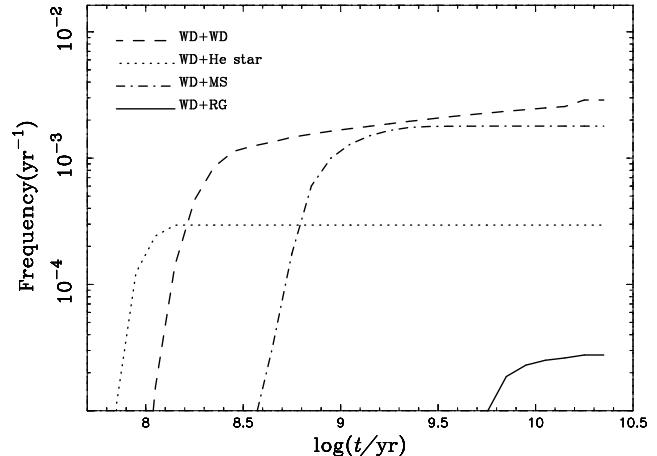


Figure 4: Evolution of Galactic SN Ia birthrates for a constant star formation rate ($Z = 0.02$, $\text{SFR} = 5 M_{\odot} \text{yr}^{-1}$). (From Wang et al., 2010b)

The observational homogeneity of SNe Ia implies that a single progenitor system may produce most or all SNe Ia. However, evidence for some observational diversity among SNe Ia, as well as evidence that SNe Ia can be produced by stellar populations that have a wide range of ages, raises the possibility that a variety of progenitor systems may be contributing.

3.2. Birthrates of SNe Ia

The observed SN Ia birthrate in our Galaxy is $\sim 3 \times 10^{-3} \text{ yr}^{-1}$ (Cappellaro and Turatto, 1997), which can be used to constrain the progenitor models of SNe Ia. Based on a detailed BPS study, Wang et al. (2010b) systematically investigated Galactic SN Ia birthrates for the SD and DD models, where the SD model includes the WD + MS, WD + RG and WD + He star channels (see Fig. 4). They found that the Galactic SN Ia birthrate from the DD model is up to $2.9 \times 10^{-3} \text{ yr}^{-1}$ by assuming that SNe Ia arise from the merging of two CO WDs that have a combined mass larger than or equal to the Ch mass, which is consistent with the birthrate inferred from observations, whereas the total birthrates from the SD models can only account for about 2/3 of the observations, in which the birthrate from the WD + MS channel is up to $1.8 \times 10^{-3} \text{ yr}^{-1}$, the WD + RG channel is up to $3 \times 10^{-5} \text{ yr}^{-1}$ and the WD + He star channel is up to $0.3 \times 10^{-3} \text{ yr}^{-1}$. The Galactic SN Ia birthrate from the WD + RG channel is too low to be compared with that of observations, i.e. SNe Ia from this channel may be rare. However, further studies on this channel are necessary, since this channel may explain some SNe Ia with long delay times. In addition, it has been suggested that both recurrent novae, i.e. RS Oph and T CrB, are probable SN Ia progenitors and belong to the WD + RG channel (e.g. Belczyński and Mikolajewska, 1998; Hachisu et al., 1999b; Sokoloski et al., 2006; Hachisu et al., 2007; Patat et al., 2007a, 2011). For other arguments in favour of the WD + RG channel see Sects. 4.2 and 4.3.

The SN Ia birthrate in galaxies is the convolution of the delay time distributions (DTDs) with the star formation history

(SFH):

$$\nu(t) = \int_0^t SFR(t-t')DTDs(t')dt', \quad (3)$$

where SFR is the star formation rate, and t' is the delay time of a SN Ia. Due to a constant SFR adopted here, the SN Ia birthrate $\nu(t)$ is only related to the $DTDs$, which can be expressed by

$$DTDs(t) = \begin{cases} 0, & t < t_1, \\ DTDs'(t), & t_1 \leq t \leq t_2, \\ 0, & t > t_2, \end{cases} \quad (4)$$

where t_1 and t_2 are the minimum and maximum delay times of SNe Ia, respectively, and the $DTDs'$ is the distribution of the delay times between t_1 and t_2 . If t is larger than the t_2 , equation (3) can be written as

$$\nu(t) = SFR \int_{t_1}^{t_2} DTDs'(t')dt' = \text{constant}. \quad (5)$$

Therefore, the SN Ia birthrates shown in Fig. 4 seem to be completely flat after the first rise.

3.3. Delay time distributions

The delay times of SNe Ia are defined as the time interval between the star formation and SN explosion. The various progenitor models of SNe Ia can be examined by comparing the delay time distributions (DTDs) expected from a progenitor model with that of observations. Many works involve the observational DTDs (e.g. Scannapieco and Bildsten, 2005; Mannucci et al., 2006, 2008; Förster et al., 2006; Aubourg et al., 2008; Botticella et al., 2008; Totani et al., 2008; Schawinski, 2009; Maoz et al., 2011). In recent years, three important observational results for SNe Ia have been proposed, i.e. the strong enhancement of the SN Ia birthrate in radio-loud early-type galaxies, the strong dependence of the SN Ia birthrate on the colors of the host galaxies, and the evolution of the SN Ia birthrate with redshift. Mannucci et al. (2006) claimed that these observational results can be best matched by a bimodal DTD, in which about half of SNe Ia explode soon after starburst with a delay time less than 100 Myr, whereas others have a much wider distribution with a delay time ~ 3 Gyr. In a further study, Mannucci et al. (2008) suggested that 10% (weak bimodality) to 50% (strong bimodality) of all SNe Ia belong to the young SNe Ia. The existence of the young SN Ia population has also been confirmed by many other observations (e.g. Aubourg et al., 2008; Cooper et al., 2009; Thomson and Chary, 2011), although with a wide range in defining the delay times of the young population.

Maoz et al. (2011) presented a new method to recover the DTD, which can avoid some loss of information. In this method, the star formation history of every individual galaxy, or even every galaxy subunit, is convolved with a trial universal DTD, and the resulted current SN Ia birthrate is compared to the number of SNe Ia the galaxy hosted in their survey. They reported that a significant detection of both a prompt SN Ia component, that explodes within 420 Myr of star formation, and a

delayed SNe Ia with population that explodes after 2.4 Gyr. Recently, a number of DTD measurements show that the DTD of SNe Ia follows the power-law form of t^{-1} (Maoz and Mannucci, 2012). The power-law form is even different from the strong bimodal DTD suggested by Mannucci et al. (2006), which might indicate that the two-component model is an insufficient description for the observational data. We also note that there are many uncertainties in the observed DTDs, which are dominated by the uncertainties in galactic stellar populations and star formation histories (Maoz and Mannucci, 2012).

Many BPS groups work on the theoretical DTDs of SNe Ia (e.g. Yungelson and Livio, 2000; Nelemans et al., 2001; Han and Podsiadlowski, 2004; Wang et al., 2009b, 2010a,b; Ruiter et al., 2009, 2011; Meng and Yang, 2010a; Mennekens et al., 2010; Yu and Jeffery, 2011; Claeys and Pols, 2011). Other theoretical DTDs of SNe Ia have been based on physically motivated mathematical parameterizations (e.g. Greggio and Renzini, 1983; Madau et al., 1998; Greggio, 2005, 2010). Recently, Nelemans et al. (2011) collected data from different BPS groups and made a comparison. They found that the DTDs of different research groups for the DD model agree reasonably well, whereas the SD model have rather different results (see Fig. 5). One of the main differences in the results of the SD model is the mass-accretion efficiency with which the accreted H is added onto the surface of the WD (Nelemans et al., 2011). However, the treatment of the mass-accretion efficiency cannot explain all the differences. Nelemans et al. are planning to do that in a forthcoming paper. For the SD model, Nelemans et al. (2011) only considered systems with H-rich donor stars, not including the He-rich donor stars (Wang et al., 2009a). It is worth noting that the He star donor channel can produce SNe Ia effectively with short delay times (accounting for 14% of all SNe Ia in SD model; Wang et al., 2010b), which constitutes the weak bimodality as suggested by Mannucci et al. (2008).

Hachisu et al. (2008) recently investigated new binary evolutionary models for SN Ia progenitors, with introducing the mass-stripping effect on a massive MS companion star by winds from a mass-accreting WD. This model can also provide a possible way for producing young SNe Ia, but the model significantly depends on the efficiency of the artificial mass-stripping effect. Additionally, Chen and Li (2007) studied the WD + MS channel by considering a circumbinary disk which extracts the orbital angular momentum from the binary through tidal torques. This study also provides a possible way to produce SNe Ia with long delay times ($\sim 1\text{--}3$ Gyr).

3.4. Candidate progenitors

3.4.1. Single-degenerate progenitors

A number of WD binaries are known to be excellent candidates for SD progenitors of SNe Ia, e.g. U Sco, RS Oph and TCrB (Parthasarathy et al., 2007). All of these binaries contain WDs which are already close to the Ch mass, where the latter two systems are symbiotic binaries containing a giant companion star (see Hachisu et al., 1999b). However, it is unclear whether these massive WD is a CO or an O-Ne-Mg WD; the latter is thought to collapse by forming a neutron star through

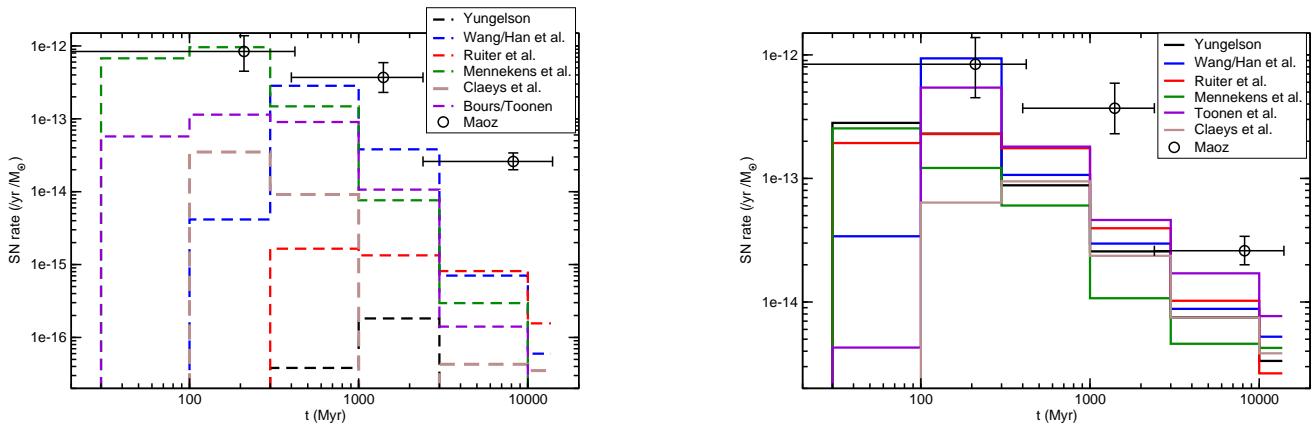


Figure 5: Rescaled delay time distributions from different BPS research groups, for the SD (left panel) and DD (right panel) models, respectively. The data points are taken from Maoz et al. (2011). (From Nelemans et al., 2011)

electron capture on ^{24}Mg rather than experience a thermonuclear explosion (for more discussion see Sect. 4.2). Meanwhile, there are also two massive WD + He star systems (HD 49798 with its WD companion and V445 Pup), which are good candidates of SN Ia progenitors.

HD 49798 is a H depleted subdwarf O6 star and also a single-component spectroscopic binary with an orbital period of 1.548 d (Thackeray, 1970), which contains an X-ray pulsating companion star (RX J0648.0-4418; Israel et al., 1997). The X-ray pulsating companion star is suggested to be a massive WD (Bisscherooy et al., 1997). Based on the pulse time delays and the inclination of the binary, constrained by the duration of the X-ray eclipse, Mereghetti et al. (2009) recently derived the masses of these two components. The corresponding masses are $1.50 \pm 0.05 M_{\odot}$ for HD 49798 and $1.28 \pm 0.05 M_{\odot}$ for the WD. According to a detailed binary evolution model with the optically thick wind assumption, Wang and Han (2010c) found that the massive WD can increase its mass to the Ch mass after only a few 10^4 years. Thus, HD 49798 with its WD companion is a likely candidate of a SN Ia progenitor.

V445 Pup is the first, and so far only, helium nova detected (Ashok and Banerjee, 2003; Kato and Hachisu, 2003). The outburst of V445 Pup was discovered on 30 December 2000 by Kanatsu (Kato et al., 2000). After that time, a dense dust shell was formed in the ejecta of the outburst, and the star became a strong infrared source, resulting in the star's fading below 20 magnitudes in the V -band (Goranskij et al., 2010). From 2003 to 2009, BVR observations by Goranskij et al. (2010) suggest that the dust absorption minimum finished in 2004, and the remnant reappeared at the level of 18.5 magnitudes in the V -band. Goranskij et al. (2010) reported that the most probable orbital period of the binary system is ~ 0.65 day. Based on the optically thick wind theory, Kato et al. (2008) presented a free-free emission dominated light curve model of V445 Pup. The light curve fitting in their study shows that the mass of the WD is more than $1.35 M_{\odot}$, and half of the accreted matter remains on the WD, leading to the mass increase of the WD. In addition,

the massive WD is a CO WD instead of an O-Ne-Mg WD, since no indication of neon was observed in the nebula-phase spectrum (Woudt and Steeghs, 2005). Therefore, V445 Pup is a strong candidate of a SN Ia progenitor (e.g. Kato et al., 2008; Woudt et al., 2009).

3.4.2. Double-degenerate progenitors

Several systematic searches for double WD systems have been made. The largest survey for this is SPY (ESO SN Ia Progenitor Survey; Napiwotzki et al., 2004; Nelemans et al., 2005; Geier et al., 2007), which aims at finding double WD systems as candidates of SN Ia progenitors. The only likely SN Ia progenitor in this sample is not a double WD system, but the WD + sdB binary KPD 1930+2752 (Maxted et al., 2000). The orbital period of this binary is 2.283 h, the mass of the sdB star is $\sim 0.55 M_{\odot}$, and the mass of the WD is $\sim 0.97 M_{\odot}$. The total mass ($\sim 1.52 M_{\odot}$) and the merging time (< 0.2 Gyr) of the binary indicate that it is a good candidate of a SN Ia progenitor (Geier et al., 2007).

Recently, some other double WD systems have also been found, which may have the total mass close to the Ch mass, and possibly merge in the Hubble-time. These include a binary WD 2020-425 with $P_{\text{orb}} \sim 0.3$ day, $M_1 + M_2 = 1.348 \pm 0.045 M_{\odot}$ (Napiwotzki et al., 2007), V458 Vulpeculae with $P_{\text{orb}} \sim 0.068$ day, $M_1 \sim 0.6 M_{\odot}$, $M_2 > 1.0 M_{\odot}$ (Rodríguez-Gil et al., 2010), a close binary star SBS 1150+599A (double-degenerate nucleus of the planetary nebula TS 01) with $P_{\text{orb}} \sim 0.163$ day, $M_1 = 0.54 \pm 0.02 M_{\odot}$, $M_2 \sim 0.86 M_{\odot}$ (Tovmassian et al., 2010), and GD687 that will evolve into a double WD system and merge to form a rare supermassive WD with the total mass at least $1 M_{\odot}$ (Geier et al., 2010). There are also some ongoing projects searching for double WD systems, e.g. the SWARMS survey by Badenes et al. (2009b) which is searching for compact WD binaries based on the spectroscopic catalog of the Sloan Digital Sky Survey.

3.5. Surviving companion stars

A SN Ia explosion following the merger of two WDs will leave no compact remnant behind, whereas the companion star in the SD model will survive after a SN explosion and potentially be identifiable by virtue of its anomalous properties. Thus, one way to distinguish between the SD and DD models is to look at the center of a known SN Ia remnant to see whether any surviving companion star is present. A surviving companion star in the SD model would evolve to a WD finally, and Hansen (2003) suggested that the SD model could potentially explain the properties of halo WDs (e.g. their space density and ages). Note that, there has been no conclusive proof yet that any individual object is the surviving companion star of a SN Ia. It will be a promising method to test SN Ia progenitor models by identifying their surviving companions.

Han (2008) obtained many properties of the surviving companion stars of SNe Ia with intermediate delay times (100 Myr–1 Gyr) from the WD + MS channel, which are runaway stars moving away from the center of SN remnants. Wang and Han (2009) studied the properties of the companion stars of the SNe Ia with short delay times (<100 Myr) from the He star donor channel, which are related to hypervelocity He stars (for more discussion see Sect. 4.5; also see Justham et al., 2009). Moreover, Wang and Han (2010d) recently obtained the properties of the surviving companions of the SNe Ia with long delay times (>1 Gyr) from the WD + MS and WD + RG channels, providing a possible way to explain the formation of the population of single low-mass He WDs ($<0.45 M_{\odot}$; for more discussion see Sect. 4.4; also see Justham et al., 2009). The properties of the surviving companion stars (e.g. the masses, the spatial velocities, the effective temperatures, the luminosities and the surface gravities, etc) can be verified by future observations.

Tycho G was taken as the surviving companion of Tycho’s SN by Ruiz-Lapuente et al. (2004). It has a space velocity of 136 km/s, more than three times the mean velocity of the stars in the vicinity. Its surface gravity is $\log(g/\text{cm s}^{-2}) = 3.5 \pm 0.5$, whereas the effective temperature is $T_{\text{eff}} = 5750 \pm 250\text{K}$ (Ruiz-Lapuente et al., 2004). These parameters are compatible with the properties of SN Ia surviving companions from the SD model (e.g. Han, 2008; Wang and Han, 2010d). However, Fuhrmann (2005) argued that Tycho G might be a Milky way thick-disk star that is coincidentally passing the vicinity of the remnant of Tycho’s SN. Ihara et al. (2007) also argued that Tycho G may not be the companion star of Tycho’s SN, since this star does not show any special properties in its spectrum; the surviving companions of SNe Ia would be contaminated by SN ejecta and show some special characteristics.⁴ Recently, González-Hernández et al. (2009) presented some evidence that Tycho G may be enriched in ^{56}Ni , which could be the result of pollution of the atmosphere with the SN ejecta.

By assuming that the companion star in the SD model is co-rotating with the binary orbit at the moment of the SN explo-

sion, the predicted rotational velocity of Tycho G is $\sim 100\text{ km/s}$ (e.g. Wang and Han, 2010d). However, the rapid rotation predicted by the SD model is not observed in Tycho G ($7.5 \pm 2\text{ km/s}$; Kerzendorf et al., 2009). This does not yet rule out that this star is the surviving companion. The inferred slow rotation of Tycho G may be related to the angular momentum loss induced by the rapid expansion of its outer shell. Recently, Pan et al. (2012) claimed that the post-impact companion star loses about half of its initial angular momentum for Tycho G, with the rotational velocity decreasing to a quarter of its initial rotational velocity, $\sim 37\text{ km/s}$, which is closer to the observed rotational velocity ($7.5 \pm 2\text{ km/s}$). Therefore, whether Tycho G is the surviving companion of Tycho’s SN is still quite debatable. The confliction might be conquered by studying the interaction between the SN ejecta and the rotating companion star.

We also note that Lu et al. (2011) recently claimed that the angle between the direction of the non-thermal X-ray arc in Tycho’s SNR to the explosive center and the proper motion velocity of Tycho G is well consistent with the theoretical predictions and simulations. This supports Tycho G as the surviving companion of Tycho’s SN. Lu et al. (2011) also estimated the parameters of the binary system before the SN explosion, which is useful for constraining progenitor models of SNe Ia.

By investigating archival Hubble Space Telescope deep images, Schaefer and Pagnotta (2012) recently reported that the central region of SNR 0509-67.5 (the site of a 1991T-like SN Ia explosion that occurred ~ 400 years ago) in the Large Magellanic Cloud contains no surviving companion star. Thus, they argued that the progenitor of this particular SN Ia is a double WD system. In a subsequent work, Edwards et al. (2012) used the same method as in Schaefer and Pagnotta (2012) on SNR 0519-69.0, which is a normal SN Ia remnant in the Large Magellanic Cloud with an age of 600 ± 200 years, and found that the 99.73% error circle contains no post-MS stars for SNR 0519-69.0. Thus, Edwards et al. (2012) claimed to rule out the symbiotic, recurrent nova, He star and spin-up/spin-down models for this particular SN. They argued that SNR 0519-69.0 might be formed from either a supersoft channel or a double WD merge. We note that, based on very short maximum spin-down times, Edwards et al. (2012) excluded the spin-up/spin-down model. However, if the spin-down time is much longer, the results in Edwards et al. (2012) might be different.

3.6. Stripped mass of companions

In the SD model, SN explosion will strip some mass of its non-degenerate companion star. By using two-dimensional Eulerian hydrodynamics simulations, Marietta et al. (2000) examined the interaction of SN ejecta with a MS star, a subgiant star and a RG star. They claimed that the MS and subgiant companions lose $\sim 10\text{--}20\%$ of their mass after the SN explosion, and the RG companion loses about 96%–98% of its envelope. In this process, these stripped material is mixed with the SN ejecta. Since these stripped material is likely to be dominated by H, this should then lead to easily detectable H emission lines in the SN nebular phase. Unfortunately, no H has ever been detected in a normal SN Ia. The most recently observational up-

⁴Pan et al. (2012) studied the impact of SN Ia ejecta on MS, RG and He star companions with the FLASH code. They quantified the amount of contamination on the companion star by the SN ejecta in their simulations, which might help to identify a companion star even a long time after the SN explosion.

per limits on the amount of H detected are $\sim 0.01 M_{\odot}$ (Leonard, 2007),⁵ which may provide a strong constraint on the progenitor model of SNe Ia. Additionally, based on the properties of the X-ray arc inside the Tycho's SNR, Lu et al. (2011) also obtained a low stripped mass ($\leq 0.0083 M_{\odot}$), consistent with that from Leonard (2007). These observational limits are inconsistent with Marietta's predictions.

Meng et al. (2007) used a simple analytical method to calculate the amount of the stripped masses. They obtained a lower limit of $0.035 M_{\odot}$ for the stripped mass, but their analytic method used oversimplified physics of the interaction between SN Ia ejecta and a companion star. Recently, many updated studies involve the effects of SN explosion on the companion star. However, more realistic stellar models for the companion star do not show stripped mass as small as that close to the Leonard's observational limits, i.e. they do not resolve the conflict between the theory and the observations (Pakmor et al., 2008; Pan et al., 2010, 2012; Liu et al., 2012b). Thus, the high stripped mass from simulations may bring some problems for the SD model. The spin-up/spin-down model may explain the lack of H or He in SNe Ia (Justham, 2011; Di Stefano et al., 2011; Hachisu et al., 2012). In addition, the mixture degree between the SN ejecta and the stripped material may also influence the detection of H or He lines in the nebular spectra of SNe Ia.

3.7. Circumstellar material after SN explosion

In the SD model, non-accreted material blown away from the binary system before SN explosion should remain as circumstellar matter (CSM). Thus, the detection of CSM in SN Ia early spectra would support the SD model. Patat et al. (2007a) found some direct evidence on CSM in a normal SN Ia, i.e. SN 2006X, which was also exceptional in its high ejecta velocity and high reddening (Wang et al., 2008b). Patat et al. (2007a) have observed a variation of Na I doublet lines immediately after the SN explosion, which is interpreted as arising from the ionization and subsequent recombination of Na in CSM. This strongly favours a SD progenitor for this SN. Patat et al. (2007a) suggested that the narrow lines may be explained by a recurrent nova. The time-variable Na I doublet absorption features are also found in SN 1999cl (Blondin et al., 2009) and SN 2007le (Simon et al., 2009). Patat et al. (2007a) argued that the CSM may be common in all SNe Ia, although there exists variation in its detectability because of viewing angle effects. However, in a subsequent work, Patat et al. (2007b) did not find the same spectral features in SN 2000cx as they did with SN 2006X, which indicates that there might be multiple SD progenitor models. Meanwhile, the derivation of smaller absorption ratio R_V (the ratio of the total to selective absorption by dust) perhaps also suggests the presence of CSM dust around a subclass of SNe Ia (Wang et al., 2009c).

More encouragingly, Sternberg et al. (2011) studied the velocity structure of absorbing material along the line of sight to

35 SNe Ia in nearby spiral galaxies via Na I doublet absorption features. They found a strong statistical preference for blue shifted structures, which are likely signatures of gas outflows from the SN Ia progenitor systems. They concluded that many SNe Ia in nearby spiral galaxies may originate in SD systems, and estimated that at least 20% of SNe Ia that occur in spiral galaxies are from the SD progenitors. Recently, Foley et al. (2012) reported that SNe Ia with blue shifted structures have higher ejecta velocities and redder colors at maximum brightness relative to the rest of the SN Ia population, which provides the link between the progenitor systems and properties of SN explosion. This result adds additional confirmation that some SNe Ia are produced from the SD model. However, Shen et al. (2012) argued that such gas outflow signatures could also be induced by winds and/or the mass ejected during the coalescence in the double WDs.

3.8. SN remnants

SN remnants (SNRs) are beautiful astronomical objects that are also of high scientific interest, since they provide direct insights into SN progenitor models and explosion mechanisms. Recent studies by Lu et al. (2011) suggested that the non-thermal X-ray arc in Tycho's SNR is a result of interaction between the SN ejecta and the stripped mass of the companion, strengthening the motivation of studying the progenitor of a SN by studying its SNR. In addition, SNRs may reveal the metallicity of SN progenitors (Badenes et al., 2008).

Circumstellar matter (CSM) is predicted by the SD model, which was responsible for creating a low-density bubble (i.e. wind-blown cavity; Badenes et al., 2007). Its modification on larger scales will become apparent during the SNR phase. One of the obstacles the SD model faces is to search for this signatures from SNR observations. Badenes et al. (2007) searched 7 young SN Ia remnants for the wind-blown cavities that would be expected in the SD model. Unfortunately, in every case it appears that the remnant is expanding into a constant density interstellar matter (i.e. there is no wind-blown cavity in these SN remnants). However, Williams et al. (2011) recently reported results from a multi-wavelength analysis of the Galactic SN remnant RCW 86 (remnant of SN 185 A.D.). From hydrodynamic simulations, the observed characteristics of RCW 86 are successfully reproduced by an off-center SN explosion in a low-density cavity carved by the progenitor system (Williams et al., 2011). This makes RCW 86 the first known case of a SN Ia in a wind-blown cavity.

3.9. Early optical and UV emission of SNe Ia

The presence of a non-degenerate companion in the SD model could leave an observable trace in the form of the optical and ultraviolet (UV) emission. Kasen (2010) showed that the collision of the SN ejecta with its companion should produce detectable optical and UV emission in the hours and days following the SN explosion, which can be used to infer the radius of the companion. Thus, the early optical and UV observations of SN ejecta can directly test progenitor models. The optical and UV emission at early times forms mainly in the outer shells

⁵Leonard (2007) obtained deep spectroscopy in the late nebular phase of two well observed SNe Ia (SN 2005am and SN 2005cf), in search of the trace amounts of H and He that would be expected from the SD model.

of the SN ejecta, in which the unburned outer layers of the WD play an important role in shaping the appearance of the spectrum. Kasen (2010) claimed that these emission would be observable only under favorable viewing angles, and its intensity depends on the nature of the companion star.

Hayden et al. (2010) looked for this signal in the rising portion of the *B*-band light curves of 108 SNe Ia from Sloan Digital Sky Survey, finding no strong evidence of a shock signature in the data. They constrained the companion in the SD model to be less than a $6 M_{\odot}$ MS star, strongly disfavouring a RG star undergoing RLOF. Recently, Bianco et al. (2011) searched for the signature of a non-degenerate companion star in three years of SN Legacy Survey data by generating synthetic light curves accounting for the shock effects and comparing true and synthetic time series with Kolmogorov-Smirnov tests. Based on the constraining result that the shock effect is more prominent in rest-frame *B* than *V* band (for details see Fig. 3 of Kasen, 2010), Bianco et al. (2011) excluded a contribution of WD + RG binaries to SN Ia explosions. However, a rather contradictory result for the shock effects was obtained by Ganeshalingam et al. (2011).

These shock signatures predicted in Kasen (2010) are based on the assumption that the companion star fills its Roche lobe at the moment of a SN explosion. However, if the binary separation is much larger than the radius of the companion star, the solid angle subtended by the companion would be much smaller. Thus, the shock effect would be lower. Justham (2011) and Di Stefano et al. (2011) argued that the donor star in the SD model may shrink rapidly before the SN explosion, since it would exhaust its H-rich envelope during a long spin-down time of the rapidly rotating WD until the SN explosion. In this condition, the companion star would be a smaller target for the SN ejecta and produce a much smaller shock luminosity than the Roche lobe model considered in Kasen (2010) (see also Hachisu et al., 2012). Therefore, the early optical and UV emission of SN ejecta may be compatible with the SD model.

In recent optical and UV observations, Wang et al. (2012) presented UV and optical photometry and early time spectra of four SNe Ia (SNe 2004dt, 2004ef, 2005M, and 2005cf) by using Hubble Space Telescope. One SN Ia in their sample, SN 2004dt, displays a UV excess (the spectra reveal an excess in the 2900–3500 Å wavelength range, compared with spectra of the other SN Ia events). In their study, the comparison object SN 2006X may also exhibit strong UV emission. The early UV emission may indicate the presence of a non-degenerate companion star in SN Ia progenitor systems.

3.10. Early radio and X-ray emission of SNe Ia

Circumstellar matter (CSM) provides a medium with which the SN ejecta can interact and produce radio synchrotron emission. Many authors have searched for early radio emission from SNe Ia, but no detection has been made (Weiler et al., 1989; Eck et al., 1995, 2002). Hancock et al. (2011) recently have used a stacking analysis of 46 archival Very Large Array observations by Panagia et al. (2006) to set upper limits on the radio emission from SNe Ia in nearby galaxies. They gave an upper limit on the SN Ia peak radio luminosity of $1.2 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1}$ at

5 GHz, which implies an upper limit on the average companion stellar wind mass-loss rate of $1.3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ before a SN explosion. Hancock et al. (2011) argued that these limits challenge expectations if the SN ejecta were encountering a CSM from the SD model.

Aside from radio emission, the interaction of SN ejecta with the CSM can also produce X-ray emission. SN shock would run into CSM and heat it to high enough temperatures ($\sim 10^6 - 10^9 \text{ K}$), resulting in thermal X-rays (Chevalier, 1990). Compared with radio emission, X-rays from SNe Ia result from a different process and from different regions in the shocked CSM. Thus, it is a completely independent method to constrain progenitor model via detecting early X-ray emission of SNe Ia. Russel and Immler (2012) recently considered 53 SNe Ia observed by the Swift X-Ray Telescope. They gave an upper limit on the X-ray luminosity (0.2 – 10 keV) of $1.7 \times 10^{38} \text{ erg s}^{-1}$, which implies an upper limit on mass-loss rate of $1.1 \times 10^{-6} M_{\odot} \text{ yr}^{-1} \times (\nu_w)/(10 \text{ km s}^{-1})$, where ν_w is the wind speed for red supergiants that ranges from 5 to 25 km s⁻¹. Russel and Immler (2012) claimed that these limits exclude massive or evolved stars as the companions in progenitor systems of SNe Ia, but allow the possibility of MS and WD as the companion.

According to the spin-up/spin-down model of SNe Ia suggested by Justham (2011) and Di Stefano et al. (2011), there is a delay between the time at which the WD has completed its mass-accretion and the time of the SN explosion. Since the matter ejected from the binary system during the mass-transfer has a chance to become diffuse, the SN explosion will occur in a medium with a density similar to that of typical regions of the interstellar medium. Therefore, the SD model may be compatible with the upper limits from SN Ia radio and X-ray detection.

3.11. Pre-explosion images

One of the methods to clarify SN Ia progenitor models is to directly detect the progenitor of a SN Ia in pre-explosion images of the position where the SN occurred. Voss and Nelemans (2008) first studied the pre-explosion archival X-ray images at the position of the recent SN 2007on, and considered that its progenitor may be a WD + RG system. However, Roelofs et al. (2008) did not detect any X-ray source in images taken six weeks after SN 2007on's optical maximum and found an offset between the SN and the measured X-ray source position. Nelemans et al. (2008) also obtained an ambiguous answer. Nielsen et al. (2011) recently derived the upper limits of the X-ray luminosities from the locations of ten SNe Ia in nearby galaxies (<25 Mpc) before the explosions, most above a few $10^{38} \text{ erg s}^{-1}$ (for details see Fig. 1 of Nielsen et al., 2011), which indicates that the progenitors of these SNe Ia were not bright supersoft X-ray sources shortly before they exploded as SNe Ia. However, the upper limits are not constraining enough to rule out less bright supersoft X-ray progenitors (Nielsen et al., 2011). Future observations may shed light on the connection between SN Ia progenitors and X-ray emission.

SN 2011fe occurred in M101 at a distance of 6.4 Mpc is the

second closest SN Ia in the digital imaging era,⁶ which was discovered by the Palomar Transient Factory survey less than a day after its explosion (Nugent et al., 2011a), and quickly followed up in many wavebands (Li et al., 2011; Nugent et al., 2011b; Smith et al., 2011; Tammann and Reindl, 2011; Patat et al., 2011b; Liu et al., 2012; Horesh et al., 2012; Chomiuk et al., 2012; Bloom et al., 2012; Brown et al., 2012a; Margutti et al., 2012). Li et al. (2011) used extensive historical imaging obtained at the location of SN 2011fe to constrain the visible-light luminosity of the progenitor to be 10–100 times fainter than previous limits on other SN Ia progenitors. This result rules out luminous RG stars and most He stars as the mass donor star of this SN progenitor. These observations favour a scenario where the progenitor of SN 2011fe accreted material either from WD, or via RLOF from a MS or subgiant companion. In a subsequent work, Liu et al. (2012) also excluded its progenitor system with the most hottest photospheres by constraining X-ray properties prior to the SN explosion.

Very recently, Horesh et al. (2012) set upper limits on both radio and X-ray emission from SN 2011fe, excluding the presence of a circumstellar matter from a giant donor star. Based on deep radio observations, Chomiuk et al. (2012) also excluded the presence of circumstellar matter. By using early optical and UV observations of SN 2011fe, Nugent et al. (2011b) excluded the presence of shock effects from SN ejecta hitting a companion, and put a strict upper limit to the exploding star radius ($\leq 0.1 R_{\odot}$), thus providing a direct evidence that the progenitor is a compact star. A recent study by Bloom et al. (2012) also ruled out a MS star as the mass donor star and seem to favor a DD progenitor for SN 2011fe (also see Brown et al., 2012a). We note that the spin-up/spin-down model potentially affects the conclusions above.

3.12. Polarization of SNe Ia

Spectropolarimetry provides a direct probe of early time SN geometry, which is an important diagnostic tool for discriminating among SN Ia progenitor systems and theories of SN explosion physics (see Livio and Pringle, 2011). A hot young SN atmosphere is dominated by the electron scattering that is highly polarizing. For an unresolved source with a spherical distribution of scattering electrons, the directional components of the electric vectors of the scattered photons counteract exactly, resulting in zero net linear polarization. However, an incomplete cancellation will be derived from any asymmetry in the distribution of the scattering electrons, or of absorbing material overlying the electron-scattering atmosphere, which produces a net polarization (Leonard and Filippenko, 2005).

SN asymmetry can therefore be measured via spectropolarimetry, since asymmetric electron scattering leads to polarization vectors that do not cancel. Most normal SNe Ia are found to be spherically symmetric (a rather low polarization, $\lesssim 0.3\%$; Wang et al., 1996; Wang and Wheeler, 2008), but asymmetry has been detected at significant levels for a range

of SN Ia subclasses, e.g. sub-luminous SNe Ia with a continuum polarization about 0.3%–0.8% (Howell et al., 2001), and high-velocity (HV) SNe Ia with a high polarization about 2%, the spectra of which around maximum light are characterized by unusually broad and highly blueshifted absorption troughs in many line features (Leonard et al., 2005). Leonard et al. (2005) claimed that the following order emerges in terms of increasing strength of line-polarization features: normal/over-luminous SNe Ia < sub-luminous SNe Ia < HV SNe Ia. They argued that the most convincing explanation for the linear polarization of all objects is partial obscuration of the photosphere by clumps of intermediate-mass elements forged in the SN explosion. For a review of SN Ia polarimetric studies see Wang and Wheeler (2008).

The explosion mechanism itself may produce asymmetry due to off-center explosion, and thus a polarization spectrum is expected (Plewa et al., 2004; Kasen and Plewa, 2005). Thus, it is possible to obtain insight into the SN explosion physics with spectropolarimetry. Meanwhile, the progenitor systems may also cause the asymmetry. The SD model provides a natural way to produce the asymmetry. The existence of a companion in the SD model may change the configuration of the SN ejecta (e.g. a cone-shaped hole shadowed by the companion), and thus a polarization spectrum is expected (Marietta et al., 2000; Kasen et al., 2004; Meng and Yang, 2010b).⁷ In addition, the DD model may also naturally result in an asymmetry of the distribution of SN ejecta. One relevant mechanism is the rapid rotation of a WD before a SN explosion, which leads to a change in the stellar shape. Another is that there may be a thick accretion disc around the CO WD, which may be an origin of asymmetry in the configuration of the SN ejecta (e.g. Hillebrandt and Niemeyer, 2000).

Livio and Pringle (2011) argued that the nature of the correlation between the polarization and the observed SN Ia properties can be used to distinguish between the SD and DD models. As a specific example, they considered possible correlations between the polarization and the velocity gradient; a SN explosion is viewed from one pole it is seen as a high velocity gradient event at early phases with redshifts in late-time emission lines, while if it is viewed from the other pole it is seen as a low-velocity gradient event with blueshifts at late phases (Maeda et al., 2010). In the SD model, it is expected that the velocity gradient is a two-valued function of polarization, with the largest and smallest values corresponding to essentially zero polarization. In the DD model, it is expected that the observed SN properties (i.e. velocity gradient) is a single-valued and monotonic function of polarization. For details see Fig. 1 of Livio and Pringle (2011).

4. Related objects

There are some objects that may be related to the progenitors and surviving companions of SNe Ia in observations, e.g.

⁶The closest SN Ia in the digital imaging era is SN 1986G that exploded in NGC 5128 at a distance of ~ 4 Mpc (Frogel et al., 1987).

⁷By using smoothed particle hydrodynamics simulations, García-Senz et al. (2012) studied the interaction of the hole, SN material and ambient medium. They concluded that the hole could remain open in the SNR for hundreds of years, suggesting the hole could affect its structure and evolution.

supersoft X-ray sources, cataclysmic variables, symbiotic systems, single low-mass He WDs and hypervelocity He stars, etc.

4.1. Supersoft X-ray sources

Supersoft X-ray sources (SSSs) are one of the most promising progenitor candidates of SNe Ia. Binaries in which steady nuclear burning takes place on the surface of the WDs have been identified with bright SSSs, discovered by the ROSAT satellite (van den Heuvel et al., 1992; Rappaport et al., 1994; Kahabka and van den Heuvel, 1997). Most of the known SSSs are located in the Large Magellanic Cloud, Small Magellanic Cloud and M31. They typically emit $10^{36} - 10^{38}$ erg s $^{-1}$ in the form of very soft X-rays, peaking in the energy range 20–100 eV.

van den Heuvel et al. (1992) proposed a model that the relatively massive WD sustains steady H-burning from a MS or subgiant donor star. They suggested that the mass-accretion occurs at an appropriate rate, in the range of 1.0 – 4.0 × $10^{-7} M_{\odot}$ yr $^{-1}$. Meanwhile, a WD + He star system has luminosity around $10^{37} - 10^{38}$ erg s $^{-1}$ when the He-burning is stable on the surface of the WD, which is consistent with that of observed from SSSs. Thus, WD + He star systems may also appear as SSSs before SN explosions (Iben and Tutukov, 1994; Yoon and Langer, 2003; Wang et al., 2009a). In addition, in the context of SSSs, the time that elapses between the double WD merger and the SN explosion is about 10⁵ yr, and during this phase the merged object would look like as a SSS (with $T \sim 0.5 - 1 \times 10^6$ K and $L_{X-\text{ray}} \sim 10^{37}$ erg s $^{-1}$), which could provide a potential test for the DD model (Yoon et al., 2007; Voss and Nelemans, 2008). Note that the Galactic interstellar absorption and circumstellar matter may play an important role in the obscuration of X-rays.

Recently, Di Stefano (2010a,b) called attention to the fact that in the galaxies of different morphological types there exists a significant (up to 2 orders of magnitude) deficit of SSSs as compared with expectations based on SN Ia birthrates from the SD model. Gilfanov and Bogdán (2010) also obtained the same conclusion, based on the study of the luminosity of elliptical galaxies in the supersoft X-ray range. However, these authors did not consider the binary evolution. A typical binary in the SD model undergoes three evolutionary stages in order of time before SN explosion, i.e. the wind phase, the supersoft X-ray source phase and the recurrent nova phase, since the mass-accretion rate decreases with time as the mass of the donor star decreases. The supersoft X-ray source phase is only a short time (e.g. a few hundred thousand years), since the SD progenitor system spends a large part of lifetime in the wind phase or recurrent nova phase on its way to SN explosion (e.g. Han and Podsiadlowski, 2004; Meng et al., 2009; Wang et al., 2009a, 2010a; Hachisu et al., 2010; Meng and Yang, 2011a). Lipunov et al. (2011) also considered that the theoretical SSS lifetimes and X-ray luminosities have been overestimated.

4.2. Cataclysmic variables

Cataclysmic variable stars (CVs) are stars that irregularly increase in brightness by a large factor, then drop back down to

a quiescent phase (Warner, 1995). They consist of two component stars: a WD primary and a mass donor star. CVs are usually divided into several types, such as classical novae, recurrent novae, nova-like variables, dwarf novae, magnetic CVs and AM CVns, etc (Warner, 1995). Among these subclasses of CVs, recurrent novae and dwarf novae are the most probable candidates of SN Ia progenitors.

Recurrent novae have outbursts of about 4–9 magnitudes, and exhibit multiple outbursts at intervals of 10–80 years (Warner, 1995). They contain a massive WD and a relatively high mass-accretion rate (but below steady burning rate). The evolution of the outburst is very fast. Since the heavy element enhancement is not detected in recurrent novae, their WD mass is supposed to increase after each outburst. Additionally, nova outbursts require a relatively high mass-accretion rate onto a massive WD to explain the recurring nova outbursts. Thus, these objects become some of the most likely candidates of SN Ia progenitors (Starrfield et al., 1985; Hachisu and Kato, 2001). However, this class of objects are rare, with ten Galactic recurrent novae, two in the Large Magellanic Cloud and a few in M31. Recurrent novae and SSSs differ in the mass-accretion rate from a mass donor star onto the WD; SSSs have steady nuclear burning on the surface of the WD, while recurrent novae happen at rates that allow shell flashes.

By modeling the decline of the outburst light curves of some recurrent novae (T CrB, RS Oph, V745 Sco and V3890 Sgr), Hachisu and Kato (2001) suggested that these WDs are approaching the Ch mass and will produce SNe Ia. Recurrent nova systems like RS Oph have been proposed as possible SN Ia progenitors, based on the high mass of the accreting WD. Patat et al. (2011a) investigated the circumstellar environment of RS Oph and its structure, suggesting that the recurrent eruptions might create complex structures within the material lost by the donor star. This may establish a strong link between RS Oph and the progenitor system of SN 2006X, for which similar features have been detected.

Recurrent nova U Sco contains a WD of $M_{\text{WD}} = 1.55 \pm 0.24 M_{\odot}$ and a secondary star with $M_2 = 0.88 \pm 0.17 M_{\odot}$ orbiting with a period $P_{\text{orb}} \sim 0.163$ day (Thoroughgood et al., 2001). The high mass of the WD implies that U Sco is a strong progenitor candidate of a SN Ia (Thoroughgood et al., 2001; also see Hachisu et al., 2000). However, the nebular spectra of U Sco displays that the relative abundance of [Ne/O] is 1.69, which is higher than that of the typical [Ne/O] abundance found in classical novae from CO WDs and suggests that U Sco has a O-Ne-Mg WD (Mason, 2011). Thus, U Sco may not explode as a SN Ia but rather collapse to a neutron star by electron capture on ^{24}Mg .

Dwarf novae have multiple outbursts ranging in brightness from 2 to 5 magnitudes, and exhibit intervals from days to decades. The lifetime of an outburst is typically from 2 to 20 days and is related to the outburst interval. Dwarf nova outbursts are usually attributed to the release of gravitational energy resulted from an instability in the accretion disk or by sudden mass-transfer via the disk (Warner, 1995). Observationally, there are a number of dwarf novae in which the WD is about $1 M_{\odot}$ (e.g. GK Per, SS Aur, HL CMa, U Gem, Z Cam, SY Cnc,

OY Car, TW Vir, AM Her, SS Cyg, RU Peg, GD 552 and IP Peg, etc). The secondaries of these WD binaries are K or M stars ($<1 M_{\odot}$). A few of these systems with early K type secondaries may have the WD mass close to the Ch mass. It has been suggested that the mass-accretion rate onto a WD during a dwarf nova outbursts can be sufficiently high to allow steady nuclear burning of the accreted matter and growth of the WD mass (King et al., 2003; Xu and Li, 2009; Wang et al., 2010a; Meng and Yang, 2010a). However, whether dwarf nova outbursts can increase the mass of a WD close to Ch mass is still a problem (e.g. Hachisu et al., 2010).

4.3. Symbiotic systems

Symbiotic systems are long-period binaries, consisting of a RG and a hot object that is usually a WD (Truran and Cameron, 1971). The hot object accretes and burns material from the RG star via stellar wind in most cases, but could also be RLOF in some cases. They usually show strong emission lines from surrounding circumstellar material ionized by the hot component, and low temperature absorption features from the RG. Symbiotic systems are essential to understand the evolution and interaction of detached and semi-detached binaries. There are two distinct subclasses of symbiotic stars, i.e. the S-type (stellar) with normal RG stars and orbital periods of about 1–15 years, and the D-type (dusty) with Mira primaries usually surrounded by a warm dust shell and orbital periods longer than 10 years. Symbiotic stars are thus interacting binaries with the longest orbital periods. Tang et al. (2012) recently found a peculiar symbiotic system J0757 that consists of an accreting WD and a RG. In quiescent phase, however, it doesn't show any signature of “symbiotic”. Thus, it is a missing population among symbiotic systems, which may contribute to a significant fraction of SN Ia. Moreover, this object showed a 10 year flare in the 1940s, possibly from H-shell burning on the surface of the WD and without significant mass-loss. Therefore, the WD could grow effectively.

The presence of both the accreting WD and the RG star makes symbiotic binaries a promising nursery for the production of SNe Ia. However, due to the low efficiency of matter accumulation by a WD accreting material from the stellar wind, SN Ia birthrate from these symbiotic systems is relative low (e.g. Yungelson and Livio, 1998).

4.4. Single low-mass He WDs

The existence of a population of single low-mass He WDs (LMWDs; $<0.45 M_{\odot}$) is supported by some recent observations (e.g. Marsh et al., 1995; Kilic et al., 2007). However, it is still unclear how to form single LMWDs. It has been suggested that single LMWDs could be produced by single old metal-rich stars that experience significant mass-loss before the central He flash (Kalirai et al., 2007; Kilic et al., 2007). However, the study of the initial-final mass relation for stars by Han et al. (1994) implied that only LMWDs with masses larger than $0.4 M_{\odot}$ might be produced from such a single star scenario, even at high metallicity environment (Meng et al., 2008). Thus, it would be difficult to conclude that single stars can produce LMWDs of $\sim 0.2 M_{\odot}$.

Justham et al. (2009) inferred an attractive formation scenario for single LMWDs, which could be formed in binaries where their companions have exploded as SNe Ia. Wang and Han (2010d) recently found that the surviving companions of the old SNe Ia from the WD + MS and WD + RG channels have low masses, providing a possible way to explain the formation of the population of single LMWDs (see also Meng and yang, 2010c). Conversely, the observed single LMWDs may provide evidence that at least some SN Ia explosions have occurred with non-degenerate donors (such as MS or RG donors). We note that Nelemans and Tauris (1998) also proposed an alternative scenario to form single LMWDs from a solar-like star accompanied by a massive planet, or a brown dwarf, in a relatively close binary orbit.

4.5. Hypervelocity stars

In recent years, hypervelocity stars (HVSs) have been observed in the halo of the Galaxy. HVSs are stars with velocities so high that they are able to escape the gravitational pull of the Galaxy. However, it is still not clear how to form HVSs (for a review see Tutukov and Fedorova, 2009). It has been suggested that such HVSs can be formed by the tidal disruption of a binary through interaction with the super-massive black hole (SMBH) at the Galactic center (GC) (Hills, 1988; Yu and Tremaine, 2003; Zhang et al., 2010).

The first three HVSs have only recently been discovered serendipitously (e.g. Brown et al., 2005; Hirsch et al., 2005; Edelmann et al., 2005). Up to now, about 17 confirmed HVSs have been discovered in the Galaxy (Brown et al., 2009; Tillich et al., 2009), most of which are B-type stars, probably with masses ranging from 3 to $5 M_{\odot}$ (Brown et al., 2005, 2009; Edelmann et al., 2005). The HVS B-type stars are demonstrated short-lived B-type stars at 50–100 kpc distances that are significantly unbound based on radial velocity alone. Their observed properties (ages, flight times, latitude distribution) are consistent with the Galactic center ejection scenario (Brown et al., 2012b). One HVS, HE 0437-5439, is known to be an apparently normal early B-type star. Edelmann et al. (2005) suggested that the star could have originated in the Large Magellanic Cloud, since it is much closer to this galaxy (~ 18 kpc) than to the GC (see also Przybilla et al., 2008). Li et al. (2012) recently reported 13 metal-poor F-type HVS candidates which are selected from 370,000 stars of the data release 7 of the Sloan Digital Sky Survey. With a detailed analysis of the kinematics of these stars, they claimed that seven of them were likely ejected from the GC or the Galactic disk, four neither originated from the GC nor the Galactic disk, and the other two were possibly ejected from either the Galactic disk or other regions.

At present, only one HVS, US 708, is an extremely He-rich sdO star in the Galactic halo, with a heliocentric radial velocity of $+708 \pm 15$ km/s. Hirsch et al. (2005) speculated that US 708 was formed by the merger of two He WDs in a close binary induced by the interaction with the SMBH in the GC and then escaped. Recently, Perets (2009) suggested that US 708 may have been ejected as a binary from a triple disruption by the SMBH, which later on evolved and merged to form a sdO star. However, the evolutionary lifetime of US 708 is not enough if

it originated from the GC. Wang and Han (2009) found that the surviving companions from the He star donor channel have a high spatial velocity (>400 km/s) after a SN explosion, which could be an alternative origin for HVSs, especially for HVSs such as US 708 (see also Justham et al., 2009). Considering the local velocity nearby the Sun (~ 220 km/s), Wang and Han (2009) found that about 30% of the surviving companions may be observed to have velocity above 700 km/s. In addition, a SN asymmetric explosion may also enhance the velocity of the surviving companion. Thus, a surviving companion star in the He star donor channel may have a high velocity like US 708.

5. Origin of SN Ia diversity

SNe Ia have been successfully used as cosmological distance candles, but there exists spectroscopic diversity among SNe Ia that is presently not well understood, nor how this diversity is linked to the properties of their progenitors (e.g. Branch et al., 1995; Livio, 2000). When SNe Ia are applied as distance indicators, the Phillips relation is adopted (i.e. the luminosity-width relation; brighter SNe Ia have wider light curves), which implies that SN Ia luminosity is mainly determined by one parameter. In an attempt to quantify the rate of spectroscopically peculiar SNe Ia in the existing observed sample, Branch et al. (1993) compiled a set of 84 SNe Ia and found that about 83% – 89% of the sample are normal. According to the study of Li et al. (2001), however, only $64\% \pm 12\%$ of the observed SNe Ia are normal in a volume-limited search.⁸ The total rate of peculiar SNe Ia could be as high as $36\% \pm 9\%$; the rates are $16\% \pm 7\%$ and $20\% \pm 7\%$ for SN 1991bg-like objects and SN 1991T-like objects, respectively. SN 1991bg-like objects both rise to their maximum and decline more quickly, and are subluminous relative to normal SNe Ia, whereas SN 1991T-like objects both rise to their maximum and decline more slowly, and are more luminous relative to normal SNe Ia. These two types of peculiar events obey the luminosity-width relation. However, a subset of SNe Ia apparently deviate from the luminosity-width relation, e.g. some were observed with exceptionally high luminosity or extremely low luminosity, which may have progenitors with masses exceeding or below the standard Ch mass limit (e.g. Howell et al., 2006; Foley et al., 2009). This implies that at least some SNe Ia can be produced by a variety of different progenitor systems, and probably suggests that SN Ia luminosity is not the single parameter of the light curve shape.

It has been suggested that the amount of ^{56}Ni formed during a SN Ia explosion dominates its maximum luminosity (Arnett, 1982), but the origin of the variation of the amount of ^{56}Ni for

different SNe Ia is still unclear (the derived ^{56}Ni masses for different SNe Ia could vary by a factor of ten; Wang et al., 2008a). Many efforts have been paid to solve this problem. Umeda et al. (1999) suggested that the average ratio of carbon to oxygen (C/O) of a WD at the moment of a SN explosion is the dominant parameter for the Phillips relation, i.e. the higher the C/O ratio, the larger the amount of ^{56}Ni , and then the higher the maximum luminosity (see also Meng and Yang, 2011b). However, 3D simulations by Röpke and Hillebrandt (2004) suggest that different C/O ratios have a negligible effect on the amount of ^{56}Ni produced. At present, the studies from the explosion models of SNe Ia indicate that the number of ignition points at the center of WDs or the transition density from deflagration to detonation dominates the production of ^{56}Ni , and consequently the maximum luminosity (e.g. Hillebrandt and Niemeyer, 2000; Höflich et al., 2010; Kasen et al., 2010).

It was claimed that the ignition intensity (the number of ignition points) in the center of WDs is a useful parameter in interpreting the Phillips relation (Hillebrandt and Niemeyer, 2000). Based on the SD model, Lesaffre et al. (2006) carried out a systematic study of the sensitivity of carbon ignition conditions for the Ch mass WDs on various properties, and claimed that the central density of a WD at the carbon ignition may be the origin of the scatter of the maximum luminosity. This suggestion was further supported by detailed multi-dimensional numerical simulations of SN explosions (Krueger et al., 2010). We note that the WD cooling time before mass-accretion is less than 1 Gyr in the simulations of Lesaffre et al. (2006) and Krueger et al. (2010). However, there are SNe Ia with the delay times ~ 10 Gyr in observations. The WDs with such a long cooling time may become more degenerate before the onset of the mass-accretion phase. Some other processes, such as carbon and oxygen separation or crystallization, may occur and dominate the properties of the CO WD (Fontaine et al., 2001). How the extremely degenerate conditions affect the properties of SNe Ia still remains unclear. The suggestion of Lesaffre et al. (2006) should be checked carefully under extremely degenerate conditions. Adopting the WD mass-accretion process in Lesaffre et al. (2006), Chen et al. (2012) recently studied the evolution of various CO WDs from the onset of mass-accretion to carbon ignition at Ch mass limit. The study shows that the carbon ignition generally occurs at the center for hot low-mass CO WDs but off-center for cool massive ones, which may provide more information for the explosion models of SNe Ia.

Some numerical and synthetical results showed that the metallicity may have an effect on the final amount of ^{56}Ni , and thus the maximum luminosity of SNe Ia (Timmes et al., 2003; Podsiadlowski et al., 2006; Bravo et al., 2010). There is also some other evidence of the correlation between the properties of SNe Ia and metallicity from observations (e.g. Branch and Bergh, 1993; Hamuy et al., 1996; Wang et al., 1997; Gallagher et al., 2008; Sullivan, 2006; Howell et al., 2009a; Sullivan et al., 2010). Podsiadlowski et al. (2006) introduced metallicity as a second parameter that affects the light curve shape. For a reasonable range of metallicity, this may account for the observed spread in the Phillips relation. Since metallicity in the Universe has evolved with time, this introduces an undesirable

⁸There is increasing evidence showing that even the normal SNe Ia exhibit diversity in their spectral features (e.g. Branch et al., 2009; Wang et al., 2009c; Blondin et al., 2012). Wang et al. (2009c) investigated 158 relatively normal SNe Ia by dividing them into two groups in terms of the expansion velocity inferred from the absorption minimum of the SiII $\lambda 6355$ line around maximum light. They claimed that, one group “Normal” consists of SNe Ia with an average expansion velocity $10,600 \pm 400$ km/s, but another group “HV” consists of objects with higher velocities $\sim 11,800$ km/s. The HV SNe Ia are found to prefer a smaller extinction ratio R_V (relative to the Normal ones), which might suggest the presence of circumstellar material (see Sect. 3.7).

evolutionary effect in the SN Ia distance method, which could mimic the effect of an accelerating Universe. We also note that Maeda et al. (2010) argued that the origin of spectral evolution diversity in SNe Ia can be understood by an asymmetry in the SN explosion combined with the observer's viewing angle. Moreover, Parrent et al. (2011) investigated the presence of CII $\lambda 6580$ in the optical spectra of 19 SNe Ia. Most of the objects in their sample that exhibit CII $\lambda 6580$ absorption features are of the low-velocity gradient subtype. This study indicates that the morphology of carbon-rich regions is consistent with either a spherical distribution or a hemispheric asymmetry, supporting the idea that SN Ia diversity may be a result of off-center ignition coupled with observer's viewing angle.

6. Impacts of SN Ia progenitors on some fields

The identification of SN Ia progenitors also has important impacts on some other astrophysical fields, e.g. cosmology, the evolution of galaxies, SN explosion models and binary evolution theories, etc (e.g. Branch et al., 1995; Livio, 2000).

Cosmology. It is feasible to improve SNe Ia as mature cosmological probes, since the dominant systematic errors are clear, which include photometric calibration, selection effects, reddening and population-dependent differences, etc. In the next decade, SNe Ia are proposed to be cosmological probes for testing the evolution of the dark energy equation of state with time (Howell et al., 2009b). The use of SNe Ia as one of the main ways to determine the Hubble constant (H_0) and cosmological parameters (e.g. Ω_M and Ω_Λ ; Riess et al., 1998; Perlmutter et al., 1999), requires our understanding of the evolution of the luminosities and birthrates of SNe Ia with cosmic epoch. Both of these depend on the nature of their progenitors. Meanwhile, the evolution of the progenitor systems or a changing mix of different progenitors may bias cosmological inferences. For a recent review of this field see Howell (2011).

Galaxy evolution. Aside from cosmology, the evolution of galaxies depends on the radiative, kinetic energy, nucleosynthetic outputs (e.g. Kauffmann et al., 1993; Liu et al., 2012a) and the birthrates of SNe Ia with time, which all depend on the nature of the progenitor systems. SNe Ia are also laboratories for some extreme physics, e.g. they are accelerators of cosmic rays and as sources of kinetic energy in galaxy evolution processes (e.g. Helder et al., 2009; Powell et al., 2011). Especially, SNe Ia regulate galactic and cluster's chemical evolution. Due to the main contribution of iron to their host galaxies, SNe Ia are a key part of our understanding of galactic chemical evolution (e.g. Greggio and Renzini, 1983; Matteucci and Greggio, 1986). The existence of young and old populations of SNe Ia suggested by recent observations may have an important effect on models of galactic chemical evolution, since they would return large amounts of iron to the interstellar medium either much earlier or much later than previously thought.

Explosion models. SNe Ia provide natural laboratories for studying the physics of hydrodynamic and nuclear processes with extreme conditions. The link between the progenitor models and the explosion models is presently one of the weakest points in our understanding of SNe Ia (Hillebrandt and

Niemeyer, 2000). Due to some uncertainties that still exist in the SN explosion mechanism itself, a knowledge of the initial conditions and the distribution of matter in the environment of the exploding star is essential for our understanding of SN explosion, e.g. the ignition density may depend on the initial WD mass, the age of the progenitor, the metallicity and the treatment of rotation in the progenitor. Moreover, different progenitor models may lead to different WD structures before SN explosion. Lu et al. (2011) recently studied the properties of the Tycho's SNR. They estimated the parameters of the binary system before the SN explosion, which may shed lights on the possible explosion models.

Binary evolution theories. The identification of SN Ia progenitors, coupled with observationally determined SN Ia birthrates and delay times will help to place meaningful constraints on some theories of binary evolution, e.g. the mass-transfer between two stars, the mass-accretion efficiency of WDs, etc (e.g. Hachisu et al., 1996; Han and Podsiadlowski, 2004; Wang et al., 2009a). Especially, it is possible that the CE efficiency parameter may be constrained (e.g. Meng et al, 2011), which is important in binary evolution and BPS studies.

7. Summary

In this article, various progenitor models proposed in the literatures are reviewed, including some variants of SD and DD models. We addressed some observational ways to test the current progenitor models and introduced some observed objects that may be related to the progenitors and the surviving companion stars of SNe Ia. We also discussed the impacts of SN Ia progenitors on some fields. The origin of the observed SN Ia diversity is still unclear. It seems likely that SNe Ia can be produced by a variety of different progenitor systems, perhaps explaining part of the observed diversity. SN asymmetric explosion coupled with observer's viewing angle may also produce the diversity. Additionally, the metallicity of progenitors may be a second parameter that affects the light curve shape of SNe Ia.

At present, the SD model is the most widely accepted SN Ia progenitor model. The advantages of this model can be summarized as follows:

- (1) The SD model is in excellent agreement with the observed light curves and spectroscopy of SNe Ia, and this model may explain the similarities of most SNe Ia.
- (2) Observationally, there is increasing evidence indicating that some SNe Ia may come from the SD model (e.g. the signatures of gas outflows from some SN Ia progenitor systems, the wind-blown cavity in SN remnant, and the early optical and UV emission of SNe Ia, etc). In addition, the SD model may be compatible with some recent observations (e.g. the lack of H or He seen in nebular spectra of SNe Ia, and the upper limits from SN Ia radio and X-ray detection, etc) by considering the spin-down time.
- (3) There are some SD progenitor candidates in observations, e.g. supersoft X-ray sources, recurrent novae, dwarf novae and symbiotic systems, etc. Meanwhile, a number of high

- mass WDs that have been accreting from a non-degenerate companion star have been found.
- (4) The observed single low-mass He WDs and hypervelocity He stars may be explained by the surviving companion stars predicted in the SD model.
 - (5) SNe Ia with long delay times can be understood by the WD + MS and WD + RG channels. In contrast, SNe Ia with short delay times may consist of systems with a He donor star in the WD + He channel, or even a massive MS donor star in the WD + MS channel.
 - (6) Besides the DD model, these observed super-luminous SNe Ia can also be produced by the SD model by considering the effects of rapid differential rotation on the accreting WD.

However, the SD model is still suffering some problems from both theoretically and observationally that need to be resolved:

- (1) The optically thick wind assumption, widely adopted in the studies of the SD model, is in doubt for very low metallicity; the low-metallicity threshold for SNe Ia predicted by theories has not been found in observations.
- (2) It is still difficult to reproduce the observed birth rates and delay times of SNe Ia. This suggests that we need a better understanding of mass-accretion onto WDs.
- (3) There is still no conclusive proof that any individual object is the surviving companion star of a SN Ia, which is predicted by the SD model. A likely surviving companion star for the progenitor of Tycho's SN has been identified, but the claim is still controversial.

Although a DD merger is thought to experience an accretion-induced collapse rather than a thermonuclear explosion, any definitive conclusion about the DD model is currently premature:

- (1) There are some parameter ranges in which the accretion-induced collapse can be avoided. Recent simulations indicate that the violent mergers of two massive WDs can closely resemble normal SN Ia explosion with the assumption of the detonation formation as an artificial parameter, although these mergers may only contribute a small fraction to the observed population of normal SNe Ia.
- (2) This model can naturally reproduce the observed birthrates and delay times of SNe Ia and may explain the formation of some observed super-luminous SNe Ia.
- (3) This model can explain the lack of H or He seen in the nebular spectra of SNe Ia.
- (4) Recent observational studies of SN 2011fe seem to favor a DD progenitor. In addition, there is no signal of a surviving companion star from the central region of SNR 0509-67.5 (the site of a SN Ia explosion whose light swept Earth about 400 years ago), which may indicate that the progenitor for this particular SN Ia is a DD system.
- (5) Some observed double WD systems may have the total mass larger than the Ch mass, and possibly merge within the Hubble-time, although there are not enough double WD systems to reproduce the observed SN Ia birthrates in the context of the DD model.

Some variants of the SD and DD models have been proposed to explain the observed diversity of SNe Ia:

- (1) The sub-luminous 1991bg-like objects may be explained by the sub-Ch mass model.
- (2) The unusual properties of 2002ic-like objects can be understood by the delayed dynamical instability model.
- (3) The spin-up/spin-down model may provide a route to explain the similarities and the diversity observed in SNe Ia.
- (4) The core-degenerate model could form a massive WD with super-Ch mass that might explode as a super-luminous SN Ia.
- (5) The collisions between two WDs in dense environments could also potentially lead to sub-luminous SN Ia explosions.
- (6) The mechanism of WDs exploding near black holes is also a potential progenitor model for thermonuclear runaway, despite of the expected low rate when a WD passes near a black hole.

To set further constraints on SN Ia progenitor models, large samples of SNe Ia with well-observed light curves and spectroscopy in nearby galaxies are required to establish the connection of SN Ia properties with the stellar environments of their host galaxies. Many new surveys from ground and space have been proposed to make strides in SN Ia studies , e.g. Palomar Transient Factory, Skymapper, La Silla QUEST, Pan-STARRS, the Dark Energy Survey, Large Synoptic Survey Telescope, the Joint Dark Energy Mission and the Gaia Astrometric Mission, etc (Howell et al., 2009; Altavilla et al., 2012). These surveys will allow comparisons via large SN Ia subsamples, and start to connect SN Ia progenitors with the observed features of SN explosions themselves, and thus to unveil the nature of SN Ia progenitors.

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